ESCOLA SUPERIOR DE TECNOLOGIA I CIÈNCIES EXPERIMENTALS

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

Photovoltaic - wind hybrid system for energy supply of an isolated consumer.

TRABAJO FIN DE GRADO

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Memory of the project

1.1. Introduction to the project

This project will mainly consists of the sizing, and analysis of a PV [1] with wind mill hybrid system, for the purpose of satisfying the demand of a client that due to its characteristics the normal "modus operandi"[2] of electrical power supply would not work because of geographical characteristics, that make the connection to the grid extremely expensive, that we will be shown on the following chapters, the most profitable way for the client is the renewable solution.

Listing of the possible solutions , and weighting their pros and cons. Showing the evolution of our selection process of the solution so it can be easily understandable, and giving the main reasons of choosing one over the other based on the our criterion.

The main effect of this kind of solution will also be discussed, first on the client itself, on an economical way being this the main reason for him considering the installation. Include inside The economical evaluation is also included (in the chapter entitled Economical aspects of the project) different parameters will be examined in respect of profitability, payback and aspects such as O&M[3] cost etc… of the money inversion needed for the installation

Secondly the effect that could have on this kind of implementation, from a rural development point of view if it spreads around the surrounding areas, on the rural areas around, and economical-social way. A brief summary is given on the actual situation in Europe in the rural areas, and their main problems and causes.

Thirdly seeing this installation from an environmental point of view. The influence and change that this theoretical installation could have on benefiting the environment due to the reduction of GHG[4] to the atmosphere. Also the possible negative effects of the named installation from its production, including the GHG emissions and other possible effects on its surrounding.

[1] PV : Photovoltaic

[2] Modus operandi: Usual way of doing an specific process

[3] O&M: Operation and maintenance

[4] GHG: Greenhouse Gases

1.2. Main goals to achieve

The main goal to achieve as we have already mentioned is to accomplish the electrical energy supply of the farm that produces dairy products.

The solution that the farmer has right now is the use of a diesel engine with a generator of around **5000W** of power. The problem with this solution is that is not good enough, the whole system does not solve his basic necessities. The voltage measured at the plug sockets of the house give **160 V**[5] of current.

Connecting to the grid is also not a possibility, because in this scenario he has two options: to pay the construction of a proper derivation to his farm, which is very costly, or bringing a cable from the closest town and suffer and extremely amount of losses.

As we can see in this scenario the most profitable way will be the isolated renewable solution. On further chapters it will be fully explained.

A criteria list will be established in order to select the solution that best adjusts to his needs, we will prioritize:

1. Proper solution to his problem
2. More energy supply security and reliability
3. Economical
4. Environment
5. Subjective aspects like: Aesthetics, personal preference from the client etc.…
6. Others

[5] In Romania the standard plug tension is at 230V

1.3. Reach of the project

In this project we will mainly focus on the design and calculations related to the PV with the windmill hybrid system. Design and provisional aspect such as choosing the protection elements, inverter, cable sizing etc.…

The following aspects will **not** be discussed in this case study: methods of installation , civil engineering aspects of the installation, deep view of the Operation and Maintenance (O&M) , disposal at the end of the cycle of life and any set of laws of the country affecting the objective of this project[6].

1.4. General overview of the area

The farm dedicated to the production of dairy products is located in Romania, near the city of **Bacâu** in the village of **Călugăreni**. Milk and related products used for the production of the dairy products, come from the animals within the farm and from other farms in the nearby areas. The farm does not only gets from its neighbours the materials needed for the production, but also food for the animals and wood.

Călugăreni village is located deep into the Neamt county. Neamt County is at the north-east of Romania, close to the Moldavian and Ukrainan borders. Neamt county is famous because it has the highest amount of churches per square area in the world. [1] It has a population of around 470.766 people.

Figure 1: Overview of the Neamt County. Source: Wikipedia Commons 2011

The biggest population inside Neamt County is the city of **Piatra Neamț,** which is also the capital of the county**,** 36 km away from the village. The village is close to the lake Bijaz which is the largest artificial lake in Romania [2] created during the construction of the

[6] In this case, any set of laws from Romania affecting the PV installation

Bicaz-Stejaru hydro-plant, the named dam has a production capability of 210 MW, generating around 500 GWh every year .

It is close to the protected national park of **Ceahlău**, which was declared as a national park in 2000, and has a surface area of around 83,96 km² or 8.396 ha[7].

Piatra Neamt the capital of the county, with a population of around 85.000 people and its economy is mainly based on industry plants around the area.

In Figure 2 we can see the overall location of the village (Red) in comparison with Piatra Neamt (Blue) and the national park Ceahlău (green). We can also see the mentioned lake on the map.

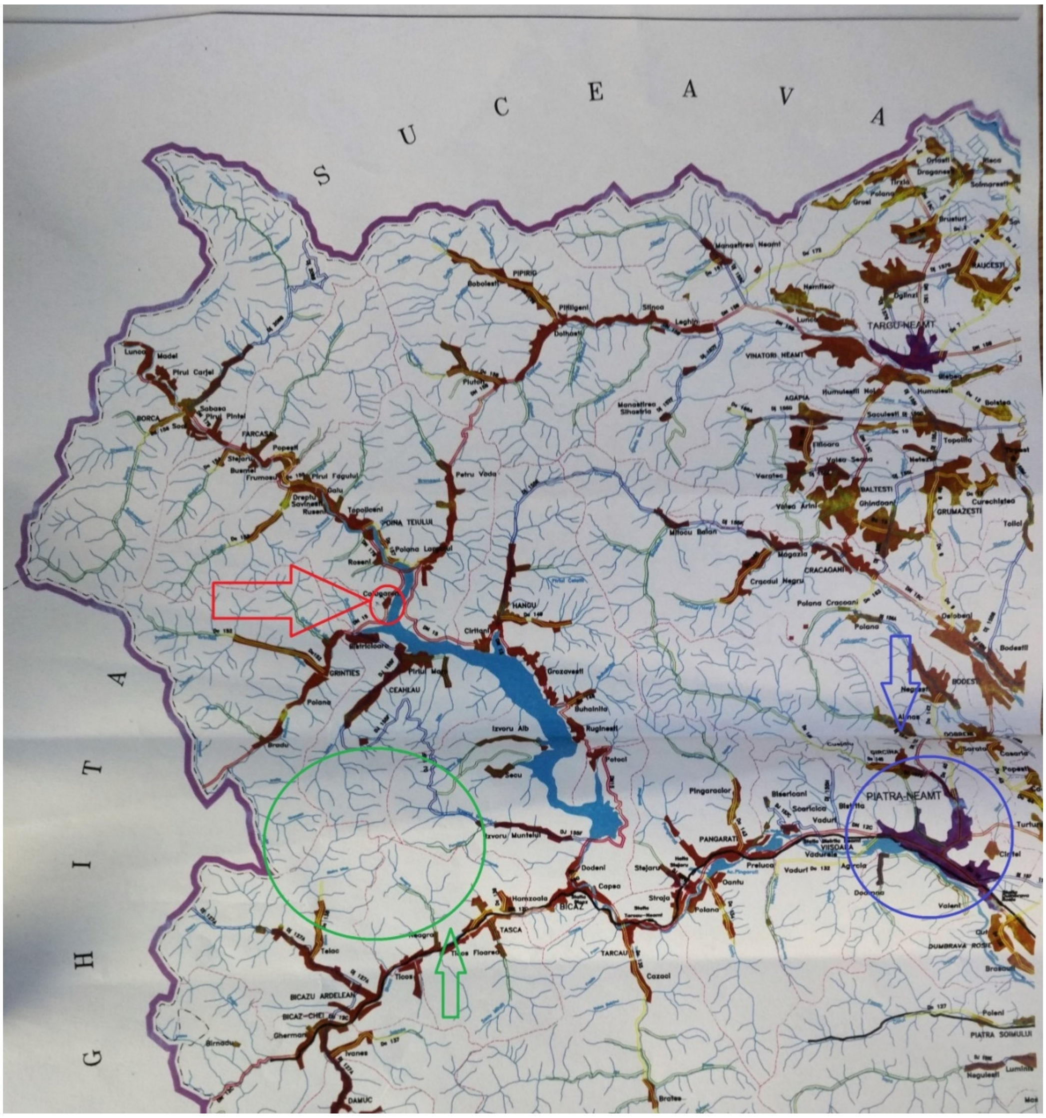

Figure 2: Location of the village

[7] Ha: hectare

1.5. State-of-art in the problem domain

As mentioned before in the main goals of this case study, the problem to is the power supply to a farm isolated from the electrical grid because of the geographical position.

The main problems to solve are the following points:

- Power supply: Right now the solution that the owner has is insufficient[8]
- Security for the electrical uses of the farm related to production

For this kind of situation in which, due factors mentioned before, and by the owner's own words, the connection to electrical grid is out of the equation. Then for this kind of situation, the solution is an off-grid generation power supply.

Off-grid generation can be achieved with the use of Photovoltaic panels. Only with the modelling of the panels we would fall short, due to the stochastic process that is solar irradiation, because aspects such as day and night cycle, clouds, weather etc... can affect it.

The night and day cycle forces the use of some kind of energy store system (ES) for making the solution viable. So batteries will also be part of the proposed solution.

As mentioned before the randomness of the solar irradiation lowers the system electricity supply security and reliability, and as established before, in our criteria one of the main points are security and reliability for him being able to secure his production system, so a windmill will be set in addition to the photovoltaic panels to raise and secure energy supply continuity.

Figure 3: A hybrid system: PV+WM[9]

[8] See part "1.1 Main goals" for further information
[9] PV+WM stand for : Photovoltaic panel plus Windmill

In addition, the farm is used during the winter day, so a heating system is in use. The system actually implemented is a boiler which works with wood. A collector will be also proposed (as an extra) to give hot water service to the house for heating purposes. On the economical part of the case study we will see if the addition of this module will be profitable or not.

Therefore the solution will be a hybrid system : A photovoltaic panel and in addition a wind mill power system as the title of this project already mentioned.

Let's see then a brief overview of the technology for this kind of systems .

1.5.1. Photovoltaic and thermo solar systems:

Sun's energy is the most abundant energy source we have on this planet 173,000 terawatts of solar energy strikes the Earth continuously. That is more than 10,000 times the world's total energy use. [3]

The technologies available for the use of the sun's energy can be divided into two categories for electrical generation:

- Photovoltaic technologies (Direct)
- Solar concentration radition (indirect)

Figure 4: Example of solar technologies. Photovoltaic solar panel (Left) CSP (Right)

Also, only the heat provided from the sun is used, with the purpose of heating water for its use. This kind of technology is called solar thermal collector.

1.5.2. Silicon properties and photovoltaic effect:

The generation of electricity in the solar panels is thanks to the photovoltaic effect, an effect present in Silicon and other materials and caused by the reaction to solar irradation.

We can divide materials in three categories, when we speak about electrical conductivity:

- Conductors
- Semiconductors
- Insulators

Silicon is a semiconductor, and like metals which are conductors, their electrical conductivity is based upon movable electrons. Although both of them are similar, they act completely different on aspects such as electrical conductivity.

In his crystal form it is stable, and forms a tetrahedral structure (like diamond). This union is extremely strong.

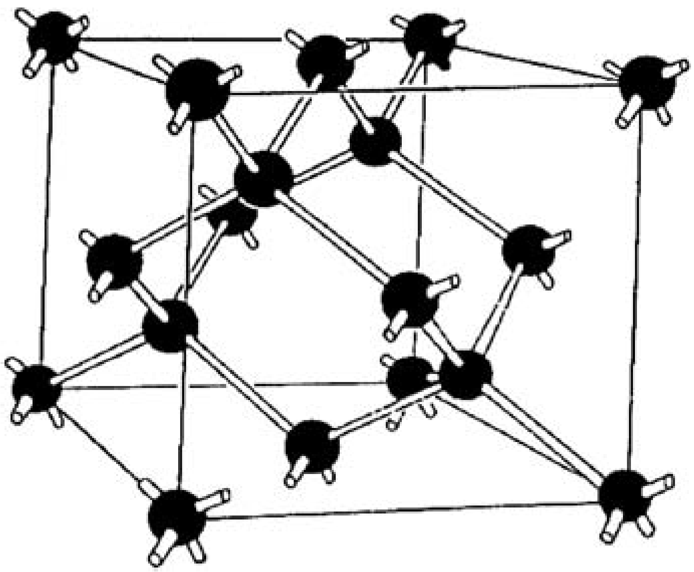

Figure 5: Tetrahedral structure of diamond. Source:[4]

When next to another Silicon atoms, and influence is being done between the electrons in the outer layers, some have more energy than others. But in semiconductors there is something what is called "band gap" between the conduction band and valence band.

For electricy (that means electrons cross the band gap) to occur, the bonds must be "forced" in some way. If we connect the silicon to an electrical potential, electrons can cross this gap and move from the "almost full" valence band to the "almost empty" conduction band. This effect is on the main characteristic of semiconductors.[4]

Doping is a technique used on silicon to amplify the effect previosly mentioned, by adding impurities to the cristal structure we can dispose of more electrons or more “holes”[10]

Common doping elements added to silicon are phosphorus which give an extra electron, also other elements are arsenic and antimony. This creates a n-type conductor.

Adding on the other hand an element from the third group of the periodic table, creates more “holes”. The elements boron, aluminum, gallium, and indium are commonly used. This creates a p-type conductor.

By disposing together, the previously mentioned elements, we have in our hand the basics of a solar cell (Figure 6)

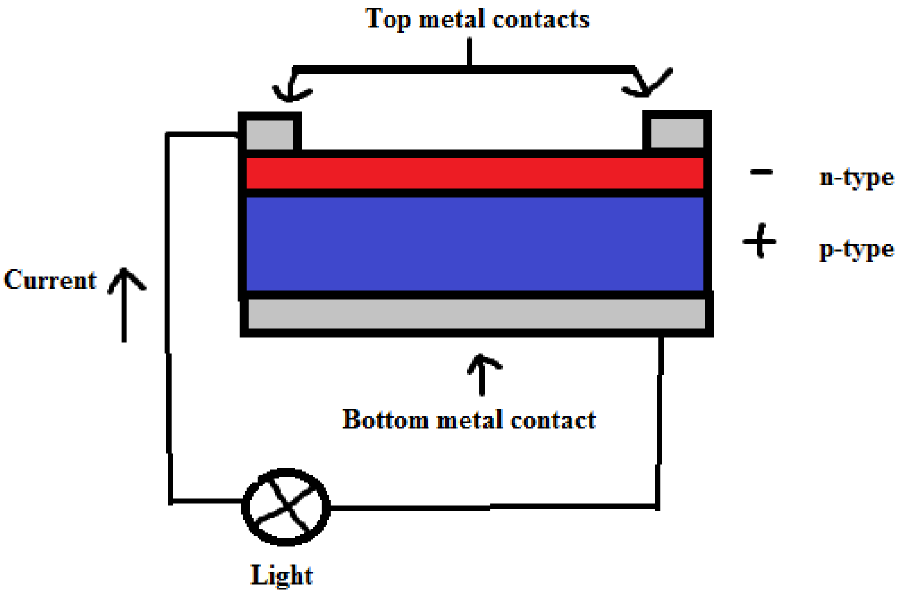

Figure 6: Basic design of a solar cell. Source: Own creation

When we put together the n and p conductors, on the union between them a depletion zone is created, due to the exchange of electrons close to the union. The part of the depletion zone close to the n type becomes positively charged and the part of the p type becomes negatively charged. This difference of polarity creates an electric field that blocks the path from the n-type electrons across the depletion zone to the p-type.

Under solar irradiation the electrons on the cell absorbs the energy from the photons coming from the sun and become free, the bond “breaks”. [5]

Due to the fact that it is not possible for the electrons to get through the depletion zone, when a cable is connected (Figure 6) the current can flow from the **n-type** (red) to the **p-type** (blue). That is the basic principle of photovoltaic solar panels.

[10] By holes we mean a state with no electrons

1.5.3. Photovoltaic cells technologies:

The most common one is the crystalline silicon. The crystals are grown using the Czochralski method. A superficial cover is also applied during the production to prevent sun's rays bouncing from the material and losing efficiency. We can mainly distinguish three main types:

- **Monocrystalline:** presents a single crystalline structure completely organized. It is obtained from pure silicon. It is the most efficient commercial technology with an efficiency around 23% by 2016.[6]. It is also the most expensive one as it is the most pure one as it is a perfectly organized crystal cell with no defects. As it is perfectly organized the cell presents homogenous color.

- **Polycrystalline:** Consists of a group of crystals of silicon but in this case it is not organized on a single macro-crystal like the monocrystalline. It is produced on a similar process to the monocrystalline cell, but, in this case the pure silicon is melted, and then is cooled down. It has a lower efficiency than the previous one but it is cheaper. Obtained from the same method as the monocrystalline but with less crystallization.

- **Amorphous silicon hydrogenated:** Disposed in a random array with a huge amount of defects and the least expensive among the three ones. It can be flexible due to the previously mentioned organization and even translucent .[7]

For the obtention of the silicon crystals **Czochralski** method is used. To grow the crystals, highly purified silicon is placed in a quartz crucible and melted. To obtain pure crystals without dislocations, a slim crystal neck of about 3 mm in diameter must be grown at a velocity of several millimeters per minute. [4]

Other type of technologies are the Thin-film technologies. These are much cheaper than the others due to the fact that they use quite less materials. The process of creation is much cheaper than the silicon crystalline.

- **Cadmium telluride (CdTe):** One type of thin-film solar cell. CdTE is a nearly ideal material for photovoltaics because it combines a serious of advantages and excellent properties, such as an excellent optical band gap and it is very easy to handle thin-film deposition processes. It has an efficiency of around 16 %. Cadmium is a rare element and toxic and not very abundant in nature categorized the number 67th in relation to its abundance.
- **Copper-indium-diselenide (CIS) and with Galium (CIGS):** Efficiency around 19% reported in laboratory. Containing gallium that in contrast with cadmium is not toxic and its disposal is much easier than the other's mentioned later.
- **Microamorphous tandem cell (a-Si) :** Combining crystalline and amorphous technologies. This technology presents the following advantages: Potential for high efficiency, low processing temperatures (below 200ºC) and reduced cost of cell

technology. The company Sanyo obtained the best results with this method, a conversion efficiency of 20.7% was achieved.

The efficiency of the cells is strictly related to how sensible they are to the wavelength from the light. Have a look at Figure 7. **Multi-junction cells** have the best efficiency among of all the types of technologies due to the overlapping of different types of materials (like a sandwich) a wider wavelength is absorbed by the cell when sun's light inflicts on the cell, reaching efficiency levels of around **46 %** (Figure 8)

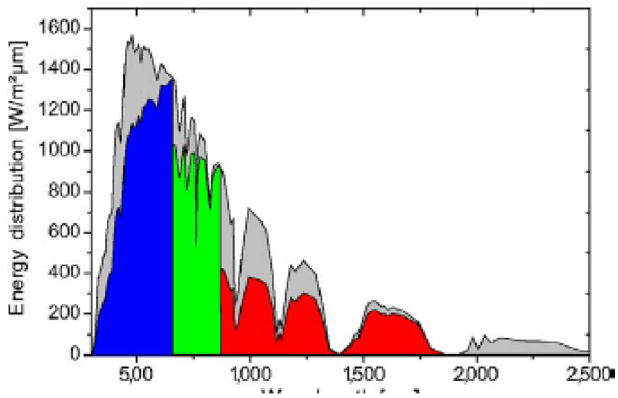

Figure 7: Wavelength absorption by cell type. Source:[4]

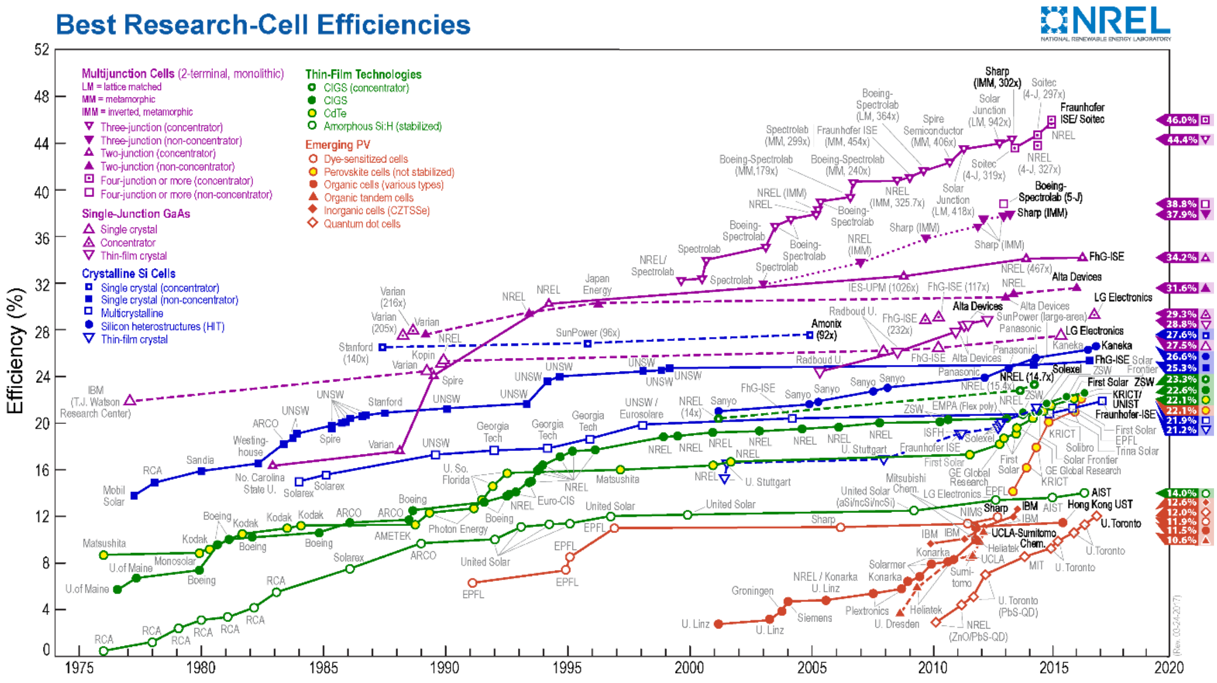

Figure 8: Efficiency chart records of the different solar cell technologies. Source: NREL

1.5.4. Wind Power technologies

Normally on isolated power system supplies, when a renewable source is installed, is installed with backups systems. A small windmill is a pretty good solution for this kind of systems. The maximum possible conversion of energy from the wind is around **59,3%,** this limit is called the Betz limit.[8]

When the sun is not shining, or in winter days when the sun irradiates with less intensity, a windmill producing electricity as a support can mean a safer supply of energy throughout the year. On periods where the solar system produces enough energy, the windmill can charge the battery system or simply is not used.

This case study will see the use of a small wind turbine, difference in technology between the big wind turbines we are used to see and small wind turbines, the working principle is exactly the same.

We consider a small wind turbine, a turbine under **16 m** of diameter for the blades and under **50 kW**.[9]

The small wind turbines can be classified in terms of the relative position of the rotating axis against the wind.

Horizontal Axis Wind Turbines (HAWT):

In this type of turbines the rotor axis is parallel to the ground. The main difference between these types of wind turbines resides mainly in the amount of blades. As the amount of blades is increased so does the area swept by the rotor, so it rotates slower which generates more torque, but it becomes worse at electricity generation.

They can be also divided in how the blades face the wind, upwind is when the “face” of the turbine is in direct opposition to the wind, and downwind is the opposite.

For electrical generation the most used one is the three-bladed in an upwind position, as it is the one which comes closer to the Betz limit.

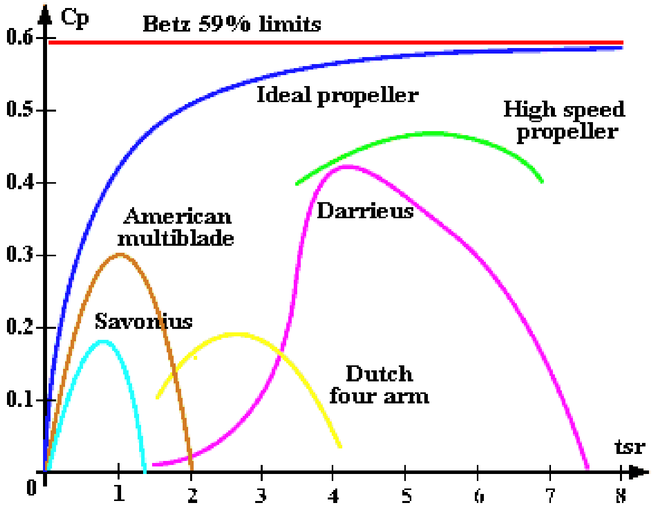

Figure 9: Bentz limit and Cp parameter by turbine type. Source: Wikipedia commons

The main elements of a HAWT are the following:

- **Rotor:** Formed by the main rotating shaft and the blades
- **Generator:** The one which converts the mechanical input into electrical output.
- **Gearbox:** Normally there is a gearbox which converts the rotation into electricity better, due to the fact that generator normally works at high revolutions, even when the blades turn slowly. The ratio of change in the gearbox multiples the rotation from the main shaft to the secondary shaft.
- **Nacelle:** It is where the gearbox and generator are installed
- **Yaw system:** It makes the rotor to follow the wind direction in order to maximize power output.
- **Control system:** Controls the general operation of all the turbines. From pitch angle to stall control. When the power output of the turbine exceeds a safety limit in pitch control, an electronic signal is generated which pitches the blades out of the wind (when the wind is too strong) reducing the angle of attack to reduce the lift. When the power is low, the opposite is done, the attack angle of the blades is changed, so it produces energy. The control is done by hydraulic control or stepped electrical motors, the latter is the predominant tendency.[10]

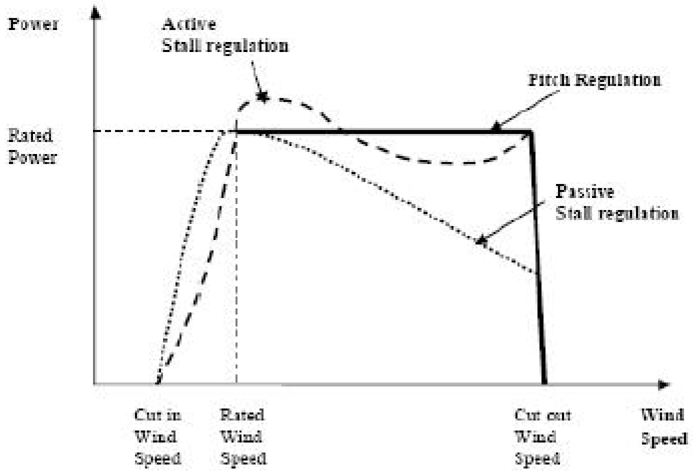

Figure 10: Passive and active stall regulation and pitch control. Source: [10]

Stall control can be done in numerous ways, from active types to passive types:

- **Passive:** They use blades attached to the hub at a fixed angle, it was designed in the case, when the wind exceeds the limit, the angle of attack to the airfoil is increased. The lift force on the blades stops stalling its rotation. The blade is slightly twisted along its longitudinal axis, to ensure that the blade stalls regularly.

- **Active:** This system resembles pitch control systems, here the blade is also pitched at low wind velocity, for the proper function, just like pitched controlled systems. The difference resides when the limit is reached, in this scenario, the stall system does the opposite of what the pitched one would do, it turns the opposite way, increasing the angle of attack, to stall the system.

Having a look at Figure 10 we can see how the different systems affect the power output. Clearly pitch control systems and active stall systems give an overall higher output, and better efficiency, the main advantage of passive stall is that when no moving parts are needed.

- **Tower:** The structure which supports the weight of all the system. The higher the turbine is located, the better, because the wind blows stronger at higher altitudes.

Vertical Axis Wind Turbines (VAWT):

Advantages of these types of wind turbines are that they do not need to track the wind due to their axis orientation and own working principle. The structural stress is much lower in these kinds of technologies, this allows to a simpler foundation and less maintenance of the gearbox. They deal better with turbulent wind and gusty wind, HAWT in these condition do not work well, the acceleration and deceleration generates a fatigue.

Main disadvantage is that the power coefficient is lower than the HAWT type see Figure 9. They tend to be less reliable than HAWT.

- **Marilyn:** Is a helix type, omnidirectional foil. Its geometrical construction provides a self-breaking mechanism.
- **Lenz:** Presents a “cup” design, it provides a very good efficiency at low wind speeds.
- **Darrieus:** It uses lift forces generated by the wind to rotate. Its main disadvantage is that there is an initial resistance that needs to be overpowered to start the rotation.
  Normally Darrieus are combined with another type of VAWT, acting as a “starter”. This saves from the need of an engine, example of a Darrieus+Savonius.
- **Savonius:** This turbine works by the difference in air pressure. One blade set comes into the wind, and the other one retreats from it. This pressure difference generates a rotation. It is used for pumping water and grinding grain in windy conditions. Savonius turbines are used whenever cost or reliability is much more important than efficiency.

1.5.5. Concentration Solar Power:

Similar to the concentrators mentioned before these technologies do not make use of the photovoltaic effect to produce effect like the ones previously mentioned. Instead they focus on the Sun’s light into a point and use it to heat liquid, which is usually water, that drives a heat engine (usually a steam turbine) connected to an electrical power generator or powers a thermochemical reaction.

- **Central receiver systems (solar tower)**: A solar power tower consists of an array of dual-axis tracking reflectors that concentrate sunlight on a central receiver atop of a tower; the receiver contains a fluid deposit, normally water or molten salts. The heat in the molten salt is then used to make steam to generate electricity. The molten salt retains heat efficiently, so it can be stored for days for its use[11]

- **Parabolic throughs**: Parabolic reflectors concentrates sun’s energy to a receiver positioned along the reflector's focal line. The energy heats the oil flowing through the tube and is the used to produce electrical energy

- **Dish Stirlings**: A dish Stirling or dish engine system consists of a stand-alone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point. The reflector tracks the Sun along two axes. The receiver is heated and this heat is used for electricity production later [11]. The stirling engine attached to the system, works with thermic variation of the liquid inside the receiver .Parabolic-dish systems provide high solar-toelectric efficiency (between 31% and 32)

Collectors:

Related to CSP[11]. Solar collectors are exclusively used to heat water. Their aesthetics is very similar to a photovoltaic panel, but their purpose is different. Collectors are installed on the roofs of houses (normally) and they use sunlight heat to heat water running along them. They can also be used for heating or cooling systems, heating swimming pools etc…

There are mainly two different technologies for water heating:

Flat-plate solar collector: The first model was developed by Hottel and Whillier in the 50's. Basically it consists of a tube running along all the area of the collector, water runs through it and the sunlight heats the tube, while heating the water in the process.

The tube is called absorber, and normally it is made of high conductive metals, like copper or aluminium, the tube is coated to maximize radiant energy absorption, and to minimize radiant emission. The module is covered by a glass, which allows the sunlight to pass, but at the same time blocks the wind from making contact with the tubes and therefore it avoids the cooling of the tube and the consequent loss in energy.

Vacuum tube: These kind of collector reduces convective and heat conduction losses by the use of vacuum inside the tubes. Each tube consists of two glass tubes, one outside, one inside. The outer tube is made of a strong transparent borosilicate glass, the inner one is made of borosilicate, also, but coated with a special coating, which boosts solar heat absorption and minimal heat reflection. Inside the tubes a copper pipe is placed, all tubes connected to a heat exchanger. The liquid inside the tubes is normally not "just water", it also prevents erosion and freezing.

The liquid evaporates because of the heat and goes up, to the copper manifold (heat exchanger) to a colder area, at the manifold it cools down, and transfers the heat to the pipe which carries the water that will be used for heating or other purposes.

This technology can achieve high temperatures. The actual vacuum is done between the two glass tubes, the irradition absorbed by the inner tube is kept inside due to the great insultaion achieve with the vacuum plus the properties from the inner tube's coating. Efficiency is around **93%** in total irradation absorbed.

This kind of technology can even work in low temperatures due to the previously mentioned insulation and great efficiency, unlike flat-plate collectors.

1.5.6. Systems depending their type of connection to the grid

When we implement the previosly mentioned technologies on a house, a hostel etc… any consumer now is producing its own energy. When producing your own energy you change

[11] CSP stands for concentrated solar power

from a central distribution type to a distributed generation type, meaning now the generations points are not focalised.

Not getting into the details, this distributed generation is seen by many as the future of distribution networks.[12] Because it would not only improve the energy independence of poorer areas, but also improve the losses during transportation (due to the fact that the source of energy is located closer to the demand). In Europe such losses represent around the **15-20%** (See Figure 7)

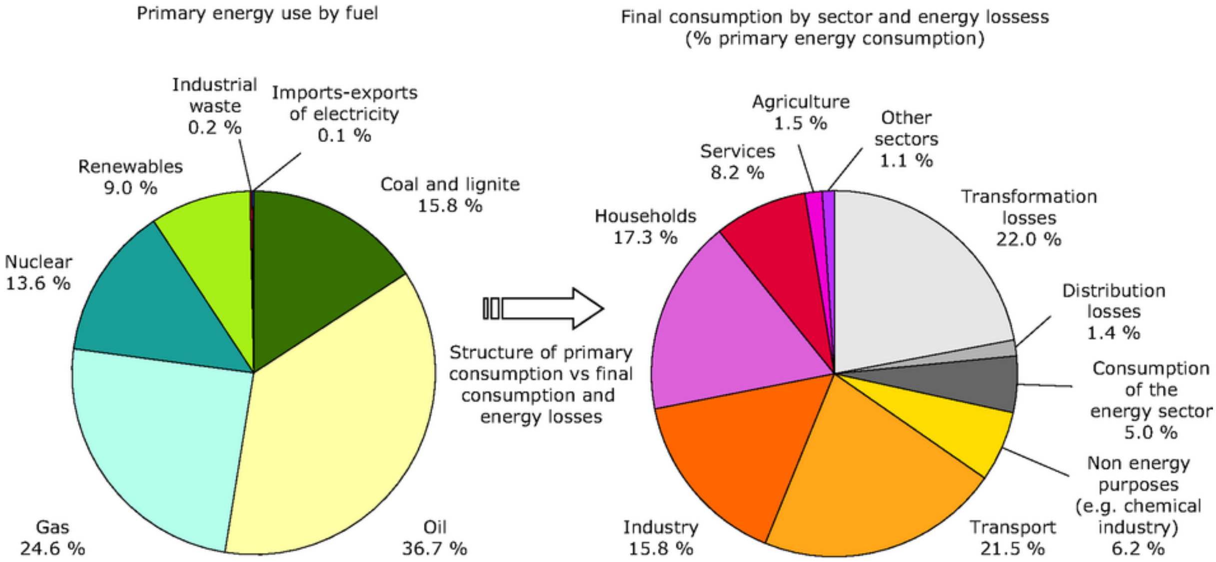

Figure 11: Primary energy use vs Final consumption. Source: [13]

As we briefly mentioned before in the introduction to this chapter, self-generation renewable installations are found normally in two possible forms:

- **Connected to the grid**: In this case there is a generation of energy, but the producer is connected to the network, this could be the case for example of a city building with roof installed solar panels. This kind of installation has the benefit that in case of excess energy, it can be injected into the network and in times of need, the electrical supply can come from the grid, eliminating the need for ES[12].

- **Off-grid:** This is the case of the objective in this case study. Off-grid installations are completely isolated from the conventional grid. Because there is no backup possibility from a grid to supply the needs, we need a way to store the energy produced during the day plus the one produced by the windmill, to be able to use it, when it is needed. Also a cogeneration system (diesel engine for example) is normally recommended for auxilliary use.

[12] ES: Energy Storage

Places like small villages could develop this configuration to the next level, by the creation of a micro-grid, where all the different generation points could be interconnected, and supply the needs to all the loads without being connected to the conventional grid.

1.5.7. Energy store systems:

Energy store systems (also called batteries, accumulators) are what make an off-grid system viable. It permits the storage of energy for later use when it is said that energy is needed. There are quite a lot of technologies (see Figure 8) available, although not all of them are suitable for the kind of project we are dealing in this case study with.

They are one of the most expensive parts of the installation, that is one of the main reasons off-grid installation need much more thoughts about their dimensioning due to the fact that they cannot store the excess energy anywhere when accumulators are full.

They can be divided also into primary and secondary energy store systems. This means primary batteries cannot be charged again when discharged, but the secondary ones can be. In this case study we will focus on secondary types.

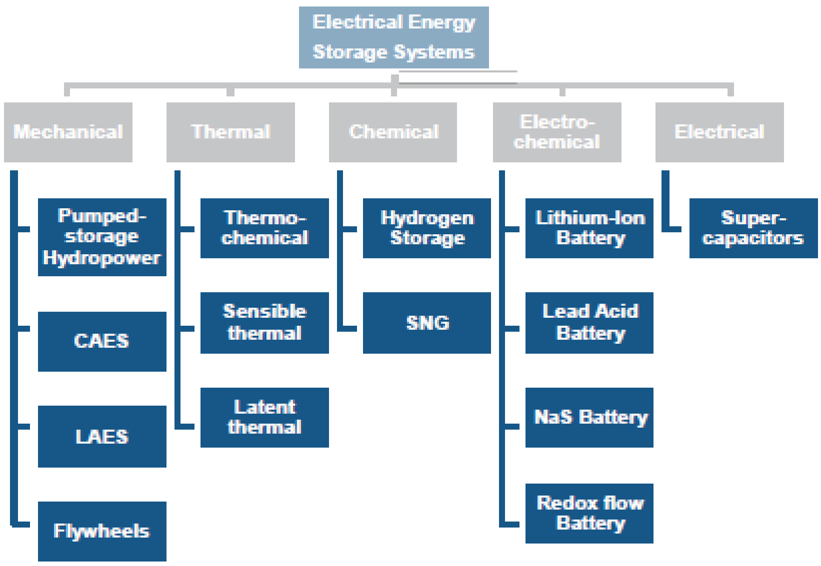

Figure 12: Overview of the different ES technologies. Source: Pwc 2015

The most used energy storage systems on photovoltaic systems are lead-acid battery and electro-chemical energy storage, due to their easy availability, it is a mature energy store technology and these kinds of systems are the ones which give the best LCOE[13] together with Li-ion batteries [14]

[13] Levelised cost of energy

1.5.7.1. Lead-Acid:

They are composed of plates of lead inside an electrolyte, for example sulfuric acid. When the battery is charged and a charge is connected to it, a reaction occurs between the lead plates and the acid, this makes the electrons to flow and feed the charge. The chemical reaction that occurs is two sided and can be reversed (charging the battery). Their basic principle does not change along the different types of lead acid batteries but it does the configuration, they can be classified in three main categories: Monobloc, stationary transparent/translucent and airtight.

Monobloc: As their own name indicates, they are disposed in an individual block, that means that there is no need to interconnect the individual cells to obtain 12,24 or 48 V. They have less capacity than airtight or translucent ones. They are mainly used on installations of low power requirement.

Stationary translucent: What are separated into cells, and the material they are covered with allows to see the level of the electrolyte inside of them. Because they are cell type batteries their voltage is 2,2 V, that is why they are connected in series to obtain the desired voltage. These types of batteries are bigger than monobloc ones and heavier, so in order to make easier the installation process they are installed without electrolyte and then filled.

Airtight: They are locked, so there is no access to their interior. They require minimum or no maintenance at all. They can be internally filled with a gel, this makes the electrolyte denser, so the electrolyte stays in place, which makes to install them in any position. The electrolyte does not need maintenance as mentioned before, but it does not support deep discharges very well. [7]

Lead batteries are cheap but their components are extremely dangerous for the environment and after their life expectancy, they are difficult to process. So in places like the European Union, they are fomenting the research on other alternatives which are easier on the environment.

1.5.7.2. Li-ion battery:

They are composed of a graphite electrode and a Lithium one. Their electrolyte is composed by a lithium salt dissolved in an organic compound. They are being heavily investigated right now, and almost every year new advances in this kind of battery are discovered, like a recent discovery from the Massachusetts Institute of Technology (MIT) were they claim they double the capacity density of Li-ion batteries [15]

Their actual popularity is not by chance, they are heavily used in all kinds of electronics, especially smartphones which is one of the reasons that this kind of storage is evolving so quickly. Right now its popularity for the chosen ES[14] for isolated photovoltaic systems is growing.

Their advantages are:

- High efficiency at charging and discharging
- No memory effect
- High capacity/volume and high capacity/mass. This one is the most attractive perspective from this tec.
- Low self-discharge rate

Their main problems are:

- Higher cost than Lead acid batteries. Although every year is slowly catching up.
- Limited number of cycles.

1.5.7.3. Other types of electro-chemical batteries:

Ni-Cad:

Similar previous technologies they have three parts: a cathode of nickel hydroxide and an anode made of cadmium, both of them inside with an electrolyte.

Very similar to lead acid batteries in term of characteristics, too. Their capacity is low-average. As being a well matured-developed technology, they are quite trustworthy for energy supply in the kind of scenarios of renewable generation systems etc…

Their main advantage is that they are kind of a superior version of lead acid batteries, although it is more expensive (price is strictly related to the use of cadmium, as this material is quite rare) than the latter mentioned, they have superior capacity compared to lead acid batteries and high number of cycles before replacement.

The big inconvenience in this battery type is the memory effect, which reduces the total capacity use of the battery and the material cadmium, which is extremely dangerous for the environment.

Ni-metal hydride:

Like Ni-Cad battery, but the cadmium is replaced with a metal hydride, which is less toxic than cadmium

Inconveniences:

- High auto-discharge
- Memory effect

[14] Energy Store

NaS:

Composed of sodium and sulfur. The temperature at which they work is around 200 Cº, this implies the need for proper security measures when using this kind of battery.

The use for PV installations in building, houses etc… is not used due to security reasons. Especially in places like the one this case study focuses on, where the risk of fire is very high.

Their efficiency is high for charge and discharge: 89-92% and long cycle life.

Redox flow batteries:

Two electrolytes react to produce the electrochemical reaction for storing and releasing energy. The contact between them is made possible through a microporous membrane that does not allow both electrolytes to mix.

Having both electrolytes separated, avoids the so called self-discharge effect, so possibly this kind of battery could be perfect (future) for the type of installation we are dealing with in this case study. But right now they still have a high price mainly due to the cost of the electrolyte.

Even some models of this technology are commercial right now, it is a pretty new technology, so in a medium-short term improvements are to be expected. Some models of this battery type are even in direct competition with Li-ion batteries.[16]

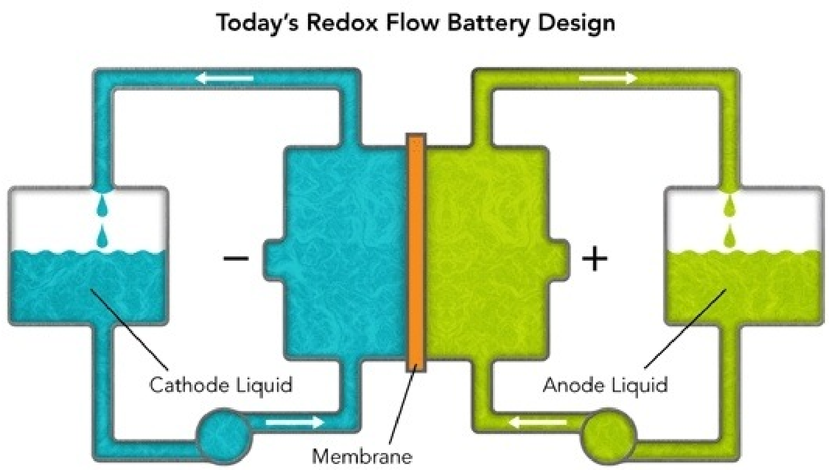

Figure 13: Redox battery simplistic view

Now let's have a look at other types of energy systems. The ones we have already seen are the ones we will consider in this case study, mainly **lead acid** and **Li-ion** because they are easier to obtain and implement, they are cheaper, and they are more convenient for the client in the end. The next few technologies, although could be used for a PV system, their implementation fells of the reach of this case study.

1.5.7.4. Mechanical energy store systems:

These kinds of systems go from the oldest type of energy store know (Pumped-Hydro-Energy Storage) to other more modern technologies such as FESS (Flywheel Energy storage)

PHS[15]:

They are by far the most matured and developed ES technology. Analysis of energy storage projects compiled by the US Department of Energy shows that pumped hydropower storage capacity in operation worldwide forms over 97% of the total storage capacity in operation[14]

PHS works by storing water on a higher height, by doing this the water on the upper level has a potential energy that can be used by simply making it fall to a lower level and through a turbine to produce electricity.

A small scale variant of PHS could be implemented, as we said, into a PV+ wind plant, but this implementation is out of the reach of this project.

Advantages:

- Mature technology
- It can store an enormous amount of energy with a lot of power output
- Quick response

Disadvantages:

- Huge initial investment cost
- Need of a good geographical place

Compressed Air Energy Storage (CAES):

Together with PHS are the most matured, and other technologies bring a cost and risk premium due to their lower levels of commercial maturity.[14]

It works by storing compressed air with the low cost off-peak energy in an underground deposit and releasing it, when needed, with a mix of fuel for later combustion in a turbine.

The main inconvenience when implementing this technology is the selection of a reservoir, it can be a natural cave of some sort but not always the case.

Pros:

- Quick response
- Long cycle life
- Low LCOE

[15] Pumped hydro energy storage

Cons:

- Huge initial cost
- All the system depends on finding a good emplacement

Flywheel Energy Storage Systems (FESS):

It uses inertia as the gimmick for energy storing. A rotating wheel that can be accelerated to a very high speed (around 100000 rpm), transforms the input electrical energy into kinetic stored energy in the rotating low –friction flywheel.

Examples of this technology can be found at CERN (European Organization for Nuclear Research) where they use this technology to compensate spikes in demand from the particle accelerator. They are used because of their quick reaction response.

1.5.7.5. Electromagnetic:

There are two commercial types of electro-magnetical energy store systems:

SMES: The functioning is very simple, it consists of coil, made of Niobium-Titanium, is cooled to very low levels of heat with liquid helium, to reach a temperature below its superconducting critical temperature, the power conditioning system and the systems which cools the coil itself. Once the coil reaches the superconducting state, it can be charged and the current will circle around till it is used.

Advantages of this system are:

- Almost instant response
- Possibility to discharge them completely at high power output
- High efficiency around 95 % and long life

Disadvantages:

- Refrigeration system is very expensive and a very high energy output is needed for maintaining the temperature.
- Still a very immature technology

Supercapacitor: It is basically a very high capacity capacitor that is connected in series-parallel, similar to the display of plates in a battery, to achieve higher voltages.

Advantages:

- Response time almost instant
- Very long life

Disadvantages:

- Very high cost for big applications
- Very low energy capacity storage
- Low capacity/volume so they tend to be much bulkier than conventional ES systems

1.5.8. Elements of a typical isolated PV generation system

Once we installed a photovoltaic solar system, our panels will start generating electricity, if we connect our panels with the batteries and the loads to feed in parallel, the following problem will occur:

- The voltage given by the PV system can be too low or to high putting in the danger the battery
- The solar PV systems give energy in the form of DC (direct current) so for a few loads that work with DC, nowadays almost all consumptions in a house are in AC.
- During the day the battery would be charged by the panels, but because of the fact that there is not any control for the charge process, when it is full, the energy will be still forced inside the battery. This is not only dangerous, but will also destroy the battery in the long run.
- Not adjusting voltage from the panels to make use of the maximum power possible for the panel, under the changing irradiance levels and adjusting to the different changes along the day with a MPPT (Maximum power point tracker) device. Lost efficiency.

So a bunch of balance of system elements will be needed for the optimal and correct use of the duo **PV+Wind** with the ES system. A charge controller (also called regulator or battery regulator) for the best use of the battery, and an inverter to convert the energy from DC to AC.

But first let's take a look at how solar panels behave under different circumstances and the different configurations. This will be relevant later when we speak about the inverter and the charge regulator.

The behavior of a solar panel is measured under certain standard conditions[7]:

- Solar irradiance: 1000 $\frac{W}{m^2}$
- Temperature: 25 ºC
- Angle of the sunlight perpendicular to the module
- Air mass: 1,5 AM

The I-V graphic of a solar module presents this form under these circumstances

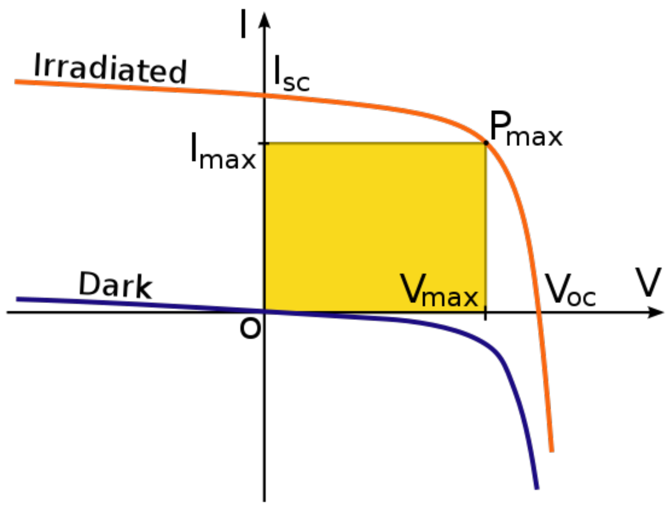

Figure 14: Solar cell V-I graphic. Source: Wikipedia Commons by original author: S-kei , svg version by Actam

We can distinguish from Figure 9 that there is a point of maximum power output from the solar cell, this operation point is what we aim for because this is the point of maximum usage and power output of the cell.

Voc is the open circuit voltage together with ***Isc,*** which is the short-circuit current, both parameters are relevant on the designing phase for making sure that on the worst scenario the other elements such as: inverter, regulator etc.… can work safely and do not break.

PVs are also connected in parallel and in series to achieve the desired current or voltage. The next Figure shows how the V-I graphic changes under the different configurations. Connecting them in a parallel array the current augments in direct relation to the amounts of panels connected. For a series connection the same thing happens, but in this case the voltage multiplies.

1.5.8.1. Inverter

This electronic component is the one responsible for converting the DC output of PV or a storage battery to AC electricity, either to be fed into the grid or to supply a stand-alone system.

Some design criteria and functionality of PV inverters are:

- efficiency: well above 90%

- voltage and current quality: harmonics and EMC,
- overload capability: some 20‑30% for grid-connected inverters, up to 200%
- for short-time overload of island inverters,
- precise and robust MPP tracking (reliably finding the overall MPP in partial shading situations),
- supervision of the grid, safety/ENS2,
- data acquisition and monitoring[4]

There are different types of inverters, depending on how they convert the wave from DC to AC. Some are grid-tie inverters, these types need a “wave example” from the electrical grid to convert the DC current to a sine wave and injecting it. They are normally used in general local electrical power generators.

The type of inverters can be classified by how they convert the wave:

- **Square wave inverters:** Normally used for isolated installations. They have low efficiency, also the shape of the wave creates a lot of harmonics, which cause sound disturbance. They are the cheapest type of inverters.
- **Sine wave inverters:** Used for grid connection PV systems. High efficiency and minimum THD[16]. Expensive in comparison with the other three.
- **Modified sine wave:** A mix between the other two. It is the sum of two square waves which is phase shifted 90 degrees relative to the other. The final wave resembles a sine wave.

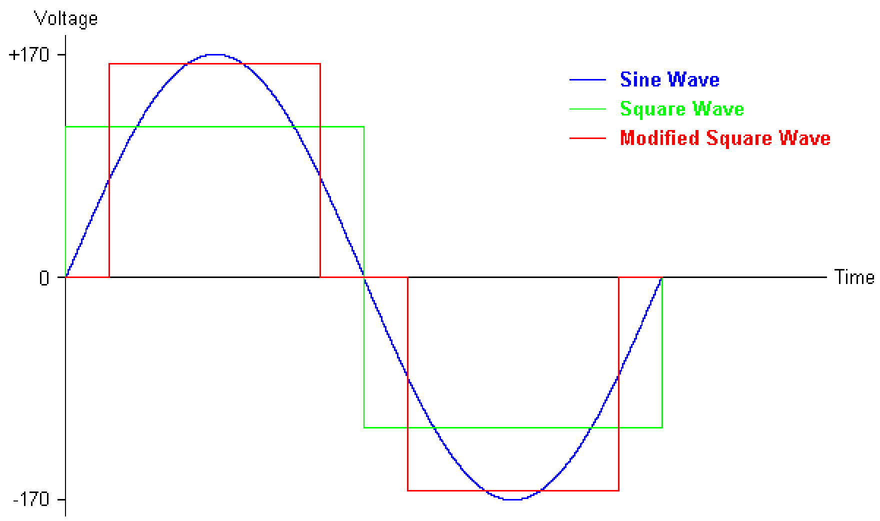

Figure 15: Different types of waves.

Not all electronics, power consuming elements are compatible with square or modified sine wave inverters.

[16] THD: Total Harmonics Distortion

With the changes in irradiation and temperature along the day, the working point of the solar panels changes, too. This change of irradiation implies a change of the point of maximum power from the solar panel. [17]

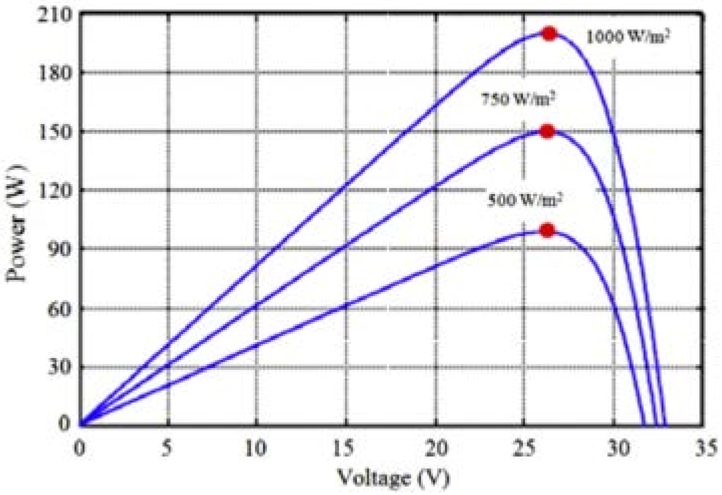

Figure 16: PV power output for different irradiation levels.

As we see in the upper figure the power output of the PV panel changes quite significantly for the different irradiation levels. The PV already has a low conversion efficiency in the range of the 9-15% normally, so the need to maximize as much as possible the energy we take from it, is crucial, by MPPT methods, Tracking systems etc…

Inverters are commonly build with a MPPT (maximum power point tracker). The method for finding this working point are different, can be divided into:

Indirect:

- **Fixed voltage method:** This technique is based on adjusting the PV system on seasonal basis. One Pmpp for winter and other one for summer for the same level of irradiance. In winter due to lower temperatures it is expected that the panel has a better performance than in summer.
  This method is very easy to implement, but as we can see the disadvantages, because of the inaccuracy of this method. Although in winter performance improves due to lower temperature, in summer also the irradiation level and hours of peak sun are much higher than in winter. Also does not take into account changes along the day etc…

- **Fractional open circuit voltage method:** The near linear relationship between VMPP and Voc of the PV array, under varying irradiance and temperature levels, has given rise to the fractional Voc method.

$$\boldsymbol{Vmpp \approx k * Voc} \quad \textbf{(1)}$$

The factor k is a constant calculated empirically, it depends on the array of the PV and irradiance/temperature. The procedure basically consists of opening the PV circuit and measuring the **Voc** (Figure 14) then once measured, applying the equation we obtained the **Vmpp** for that working point. The problem of this method is that there is a power loss due to that circuit is opened.[17]

Direct: These methods make use of processors to read and compare the results in real time. They are much more accurate than the previous ones.

- **Perturb and observe method :** This method consists of perturbing the PV array's terminal voltage periodically, and then it compares the PV output power with that of the previous cycle of perturbation[17]

  Once it has done the perturbation measures the power and compares it to the previous measured power. If power has increased but for example the voltage does not, then it will add a bigger perturbation for the next cycle. See Figure 17

Figure 17: Perturb and observe algorithm. Source: [17]

- **Incremental conduction method:** This algorithm is derived by differentiating the PV array power with respect to voltage and setting the result to zero.

$$\frac{dP}{dV} = \frac{D(V*I)}{dV} = I + V * \frac{dI}{dV} = 0 \text{ at the MPP} \qquad \textbf{(2)}$$

Organizing the equation we obtain.

$$-\frac{I}{V} = \frac{dI}{dV} \qquad (3)$$

The inverter will proceed and compare the result following its internal algorithm. It works measuring the instantaneous V and I of the panel, and it compares it with a value of reference from a previous working point. By following a simple logic structure, it compares the values and depending the result amplifies or reduces the voltage. If everything is the same, the new measured values are the new reference values.

These are some examples of MPPT methods, but there are much more methods and variations of the ones exposed. The investigation and advances for this kind of methods are still being made.

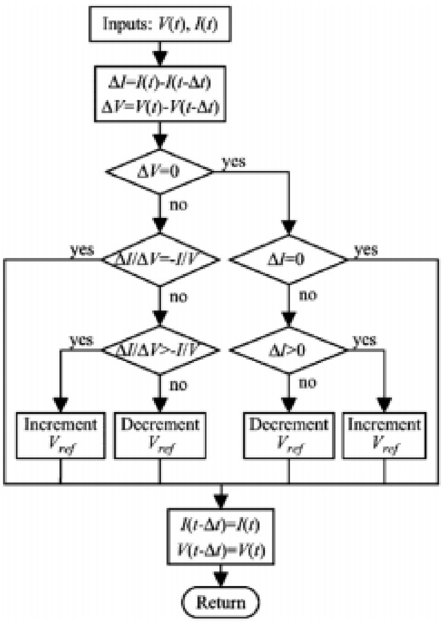

Figure 18: Algorithm for incremental conduction method. Source:[17]

The inverter can be installed in different kind of ways, what brings advantages or disadvantages, depending on how many modules it collects. Usual installation array:

- **Central:** All PVs are connected to one central inverter. This configuration requires a big inverter. The bigger the inverter the better efficiency we get. Also having only one inverter lowers the overall price, bigger inverters have a lower LCOE too, inverters from 10 to 100 kW having a LCOE of **10 cents of €/W**, in comparison a 5 kW having **22,8 cents/W** (German market data) [15] .

  The disadvantage of central inverters is that the MPPT controls all PV panels as one, meaning that panels which are receiving more or less solar energy due to different reasons, they are not making use of their maximum possible power output.

- **String:** Normally PV panels are connected first in series a bunch of them to achieve a desired voltage. These strings are connected to an inverter in this configuration type. The range of power are from 0,5 to 3 kW.

  This configuration is used when within the same installation are panels which orientation/ inclination are different or shadows that cannot be avoided. This is due to the previously mentioned, in central inverter areas where panels may have different working points are not regulated, this configuration pretends to plan earlier which possible panels could have a different working point and try to make all panels work at MPP.

- **Individual:** Every solar panel is connected to a micro inverter. This configuration tries to make all panels work at MPP. The inverter is pretty small, so it can be within the panel's configuration panel itself.

  The main inconvenience of this configuration is, that the cost of installing all those inverters is pretty high, but also more output is taken from the panels thus more kWh are produced due to all of them working at MPP.

  Also maintenance is more difficult due to the more amounts of inverters, that due to statistics, the more there are, it is more likely to break.

1.5.8.2. Regulator

This electronic device is used to manage and protect from overcharge and from very deep discharges of the battery system. Normally it is installed in isolated installations, because this kind of installation requires a battery system, in order to control the charge of the battery system.

There are two types of regulators:

- **Series regulator:** It cuts the current to the battery before it overcharges, it means when the battery has reached its maximum.
- **Shunt regulator:** This regulator dissipates power, to eliminate the excess of energy produce. It consists of a transistor in parallel with the photovoltaic panel.

Furthermore depending on the voltage input they allow:

- **PWM regulator**: It is in essence a switch that connects a solar array to the battery. The result is that the voltage of the array will have to be the one of the battery system.
- **MPPT regulators:** This regulator makes to use the previously mentioned MPPT power control for the arrays of solar panels, therefore they harvest the maximum energy possible from them. They also tolerated voltage inputs higher to the one used in the battery system, what allows to connect more panels in series to the regulator.

1.5.9. Protection elements in a PV system

Let's speak about shading before entering into the typical protection elements of a PV. Shading occurs when something (there are clouds, tree's branch, snow etc..) blocks a cell from a solar panel or an entire module.

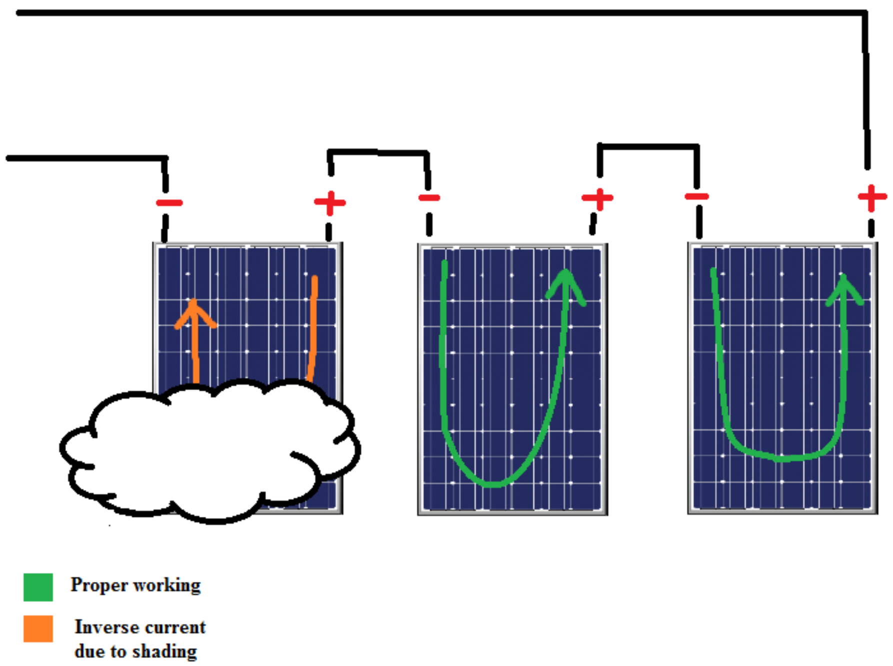

Figure 19: Shading effects. Source: Own creation

In Figure 19 we can see a simplified version of what can happen. An object blocks a cell or a bunch of them, it causes a reduction of the total irradiation on the affected cells, lowering their voltage output.

The rest of the module's cells are working on normal conditions, so their functioning is unaffected by the blocking object. This difference in voltage in cells of the same module can cause that the current instead of following the usual path, it goes backwards. This supposes a reduction not only in production, but now the panel is consuming electricity instead of producing it, what raises the temperature inside the cells, what puts in danger the cells.

To prevent this kind of situation and protect the panels, diodes are installed on the following way:

- **By-pass diode:** Located inside the junction boxes in the panels. Connected in parallel with series of cells of the solar panel and series of panels. Normally around one by-pass diode per 20-14 cells.
  In case of the solar panel due to shading, when connected in series with others see Figure 19, the by-pass diode opens and is the easier path for electricity disconnects the panels from the series.

Normally a group of by-pass diodes are installed in every solar panel, making able to "jump" series of cells which work in reverse.

- **Blocking diode:** They do a similar job to by-pass, but in this case they protect strings of panels from other panels when they are in parallel. Let's see an example for the better understanding.

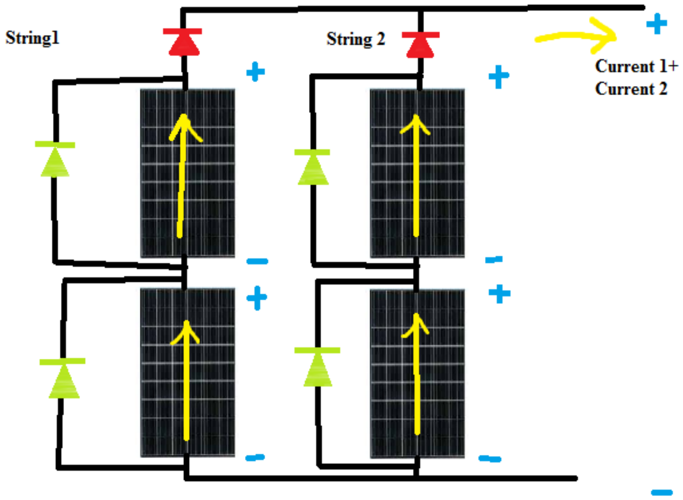

Figure 20: Diodes disposition in solar panels. Source: Own creation

Looking at Figure 20 we can see, that under normal circumstances the current (Yellow) will flow as it is displayed. Shadowing as we saw previously, that panels in one string start to go on reverse, the by-pass diode (Green) will open and "cuts" the malfunctioning panel.

In the scenario that a string of panels were at a lower voltage than another string, could cause also that the panels with higher voltage "tried" to feed the lower voltage panels string. This is solved by a blocking diode (Red), in this case the diode will block all currents coming from other strings to the string is located.

All these diodes consume some voltage, causing a loss, so the voltage and the sizing should take in mind these losses. When a diode is active, some power output potential is lost but this loss is preferable to the possible damage to the panel.

1.5.9.1. Elements of protection for the line and systems

A very basic overview on the other elements to install are there in order to protect the line from short-circuit and overcurrent.

- **Circuit breakers:**
  These elements protect from overcurrent and short-circuit. They have two mechanisms for opening the circuit, one thermic and another magnetic.

The magnetic circuit is composed of an electromagnet and it protects against short-circuits. When a defined multiply of current (established by the manufacturer) is achieved, the magnetic circuit opens.

Second, the thermic device protects against overcurrent by a bimetallic sheet, which is heated, as they are different metals, it deforms when a certain current passes through it for a certain amount of time, opening the circuit.

- **Fuses:**
  Dispositive that opens the circuit when a certain current is exceed. They are composed of an outside insulator (made of ceramic, plastic or glass) with the conductive material inside. When the current overpasses the established limit, the conductor burns inside, and opens the circuit.
  Once fused, the fuse must be replaced. They are located between the photovoltaic panels and the regulator, between the regulator and batteries and between the batteries and the inverter.

These two elements are normally combined to save money and better protection of the installation. When an installation exceeds 48 V, it will also need a grounding plus a differential to secure against indirect contacts[7]

Although the solar panels will need some kind of grounding when they exceed the 48 V limit. The masses of the solar panels, regulator and other elements should be connected to a grounding.

Protections inside the house itself enter in the category of low voltage and normally has its own legislation. This project will not define those protections as it falls out of reach.

1.6. Justification of the off-grid solution

Before beginning with the design alternatives and final design, the off grid solution will be justified in comparison to the grid connected one.

The cost of connecting the farm to the grid is very costly, due that the closest point of access to the electric network is at least 2 km away, being at least 126.000 € the grid connection alternative (prices provided by E·ON Bacau) almost double the price of the off-grid solution (See 7.1 for more information)

Also the location of the farm should be taken into account, it is surrounded by forests and located on a high, pretty hard to access position by normal means. All these characteristics could possible imply a higher cost on the grid connection alternative (due to fees, installation costs, extra working labour etc…)

So it is considered that from what it has been seen that the off-grid solution is not only justified due that implies a better profit ,but, in addition implies less environment destruction (trees cut to be able to connect the grid with the farm).

1.7. Design alternatives to be considered

We can define a series of alternatives to solve the farm's energy needs. As we mentioned earlier the energy needs are mostly electrical, but there is also a small energy requirement of heat energy in winter (heating system).

Then the difference between the different alternatives will be on how we distribute the hybrid system, by distribution of the hybrid system is meant the importance we will give to the wind turbine on the energy production aspect.

As we defined previously on the criteria for the installation sizing, a hierarchy is established:

- Proper solution to his problem
- More energy supply security and reliability
- Economical
- Environment
- Subjective aspects like: Aesthetics, personal preference from the client etc.…
- Others

So all alternatives will provide a solution to the farm problem (energy demand) but gives a higher share to the wind turbine on the electricity production aspect, which can mean more energy security and reliability.

The number of cloudy days in Neamt County along the year is pretty high, which affects the solar panels production.

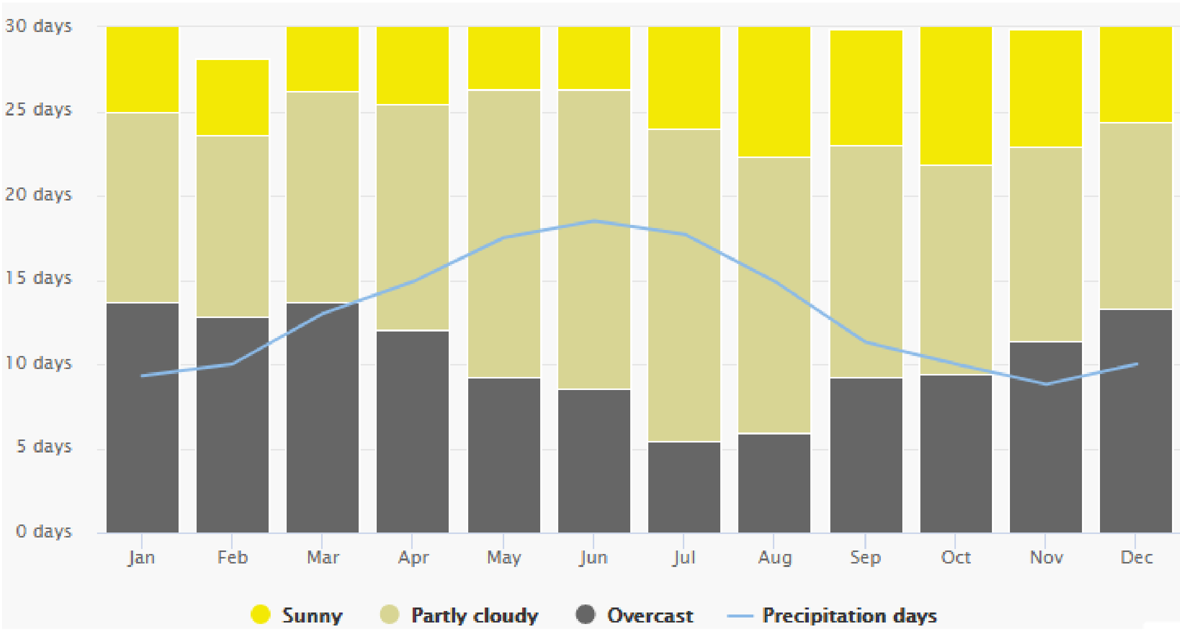

Figure 21: Forecast for Neamt county. Source: Meteoblue

Watching Figure 21 we can see the forecast per month , In Figure 22 can be seen that the amount of cloudy days are pretty high, the amount of cloudy days is also higher in the critical months (those with the least solar irradiation) which is almost 50% of the days in the month of January. These cloudy days affect solar panels production, reducing it or almost making them to no produce at all.

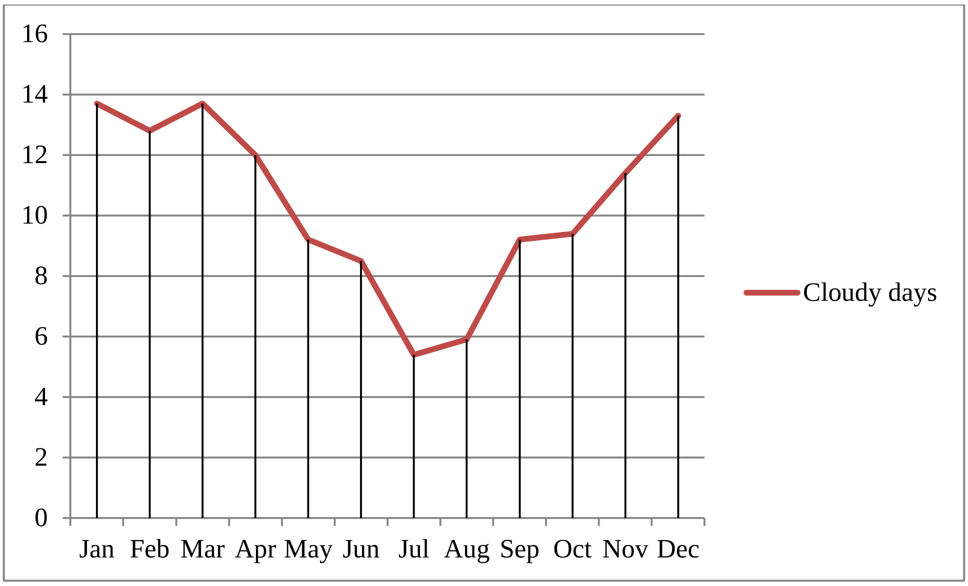

Figure 22: Cloudy days by month. Source: Own creation

The wind turbine gives more energy production security, as not only trust we energy production to an individual source (photovoltaic), although solar panel production will be the main production source.

Design alternatives:

- All solar panels
- Solar panels+ Small wind turbine 750 W
- Solar panels + Small wind turbine 3000 W
- Solar panels + Small wind turbine 6000 W
- Collectors+ Solar panels

The design alternatives will now be compared to the different design alternatives. The criteria previously mentioned (see Page 12) will be used to select among the possible alternatives.

Checking the Calculations chapter, it is needed to entirely understand aspects such as: Power demands, selection between elements….

1. All solar panels:

The very first solution and the most direct is to supply the installation solely by solar panels.

This could be achieved by the installation of 59 solar panels **TM-M672340** of 340 W from the company **Tamesol**. This method involves the least inversion (see Table 1) in comparison with the other design alternatives, due to the fact that the installation of solar panels itself is the cheapest solution, but the problem with this design is that it does not secure a continuous supply of energy around the year for the reasons we have seen before.

The forecast is not very favourable to a solar solution only, so some kind of backup from a wind turbine will be needed for securing a constant production following the criteria.

2. Solar panels + Small wind turbine 750 W:

Another possible solution could be the installation of solar panels plus the addition of a small wind turbine of 750 W, model **LE-600** from the British company **Leading Edge**.

The addition of this turbine will change the number of panels needed from 58 to 59, so the actual difference almost disappears. The inversion on the other hand is higher in comparison to solely solar panels solution, in addition, plus 1124.39 € is needed. The inversion includes the price of the turbine plus the regulator that is sold apart.

The small wind turbine helps charging the battery system, helps in critical months, when the days are shorter and there are more cloudy days.

3. Solar panels + Small wind turbine 3000 W:

The third design alternative is the installation of a wind turbine of 3000 W model **E-30 PRO 48 V** from the company **Enair,** plus the solar panels previously mentioned.

As it is a bigger turbine, the amount of panels needed to install changes from 59 to 52, and an inversion of **4975.76 €** more in comparison to the first option.

This solution gives much safety and security for energy supply during the critical months.

4. Solar panels + Small wind turbine 6000 W:

If installing an even bigger turbine, the proposed model **Bornay 6000 W (48 V)** would be from the company **Bornay** in this case.

With this solution we give a much bigger share to the wind energy production. The amount of panels to install is **43**, and an additional inversion of **6911,80 €.**

	Power demand (Wh)	Panels Needed	Panel Power (W)	Difference amount of panels (%)	Wind turbine cost (€)	Regulator cost (€)	Money Inversion (€)
No turbine	38088,18863	59	340	0	0,00 €	No needed	0,00 €
750 W Turbine	37160,60577	58	340	1,694915254	987,09 €	266,50 €	1.124,39 €
3000 W Turbine	33401,38221	52	340	11,86440678	5.880,16 €	Included with turbine	4.975,76 €
6000W Turbine	27524,85101	43	340	27,11864407	8.979 €	Included with turbine	6.911,80 €

Table 1: Comparison of the different designs.

The following additional design option will be mentioned, although it will not be considered in the installation as its design fells out of this project reach:

5. **Collectors + Solar panels:**

The industrial boiler consumes the most energy out of all devices (see Power needs of the installation), which could be fed by a series of collectors (vacuum or simple ones) connected in series and parallel.

Since collectors have much higher efficiency at converting energy from the sun to heat energy than solar panels, this application could be interesting.

In addition, solar panels feed the rest of the consumptions in the house and the industrial fridge. But as mentioned before this design is only mentioned as a possible solution, but it will be not extended or considered as a solution, as it was previously stated.

1.8. Description of the final solution.

Before exposing the proposed solution, let's compare and select the best design solution.

1.8.1. Comparison and selection of the best design

All the design alternatives achieve to provide energy to the farm accomplishing with the most important criteria established. And all of the solutions are environmentally-friendly.

Therefore the selection among the different designs will according to the rest of the criteria. The second criterion states that the solution should grand supply energy safety and reliability, then we can discard the all solar panels solutions, because of solely focusing on solar energy and taking into account the previously mentioned, it will not provide a continuous supply along the months.

By a similar reason, the second design option of solar panels plus a small turbine of 750 W can be discarded, too. Although it gives more energy safety, the difference is small, and the addition of the turbine is almost as the first design with an increased inversion, that makes almost no difference.

Then the final design solution will be between the third and fourth solutions. The difference between them is just the installation of a bigger turbine 6000 w and a smaller 3000 w, for the 4º and 3º solutions, respectively.

But the fourth design requires a bigger inversion Table 1 (see third criterion), so the third solution will be chosen, since it has the best balance out of the four solutions according to the criteria.

1.8.2. Final design solution

The chosen design is then the installation of 52 solar panels of the brand **Tamesol** model **TM-M672340** of 340 W. In addition, to make the hybrid system, a 3000 W wind turbine of the brand **Enair** model **E-30 PRO** is required. The reason followed upon choosing the solar panel model can be seen deeply explained at Selection of solar panel model.

The solar panels will be installed at a 50º degree angle to the ground, on the roof, facing to south. The roof is constructed with a 40-45º degree angle. The separation among panels, starting from the one located on the lowest point of the roof to avoid shadowing is of at least 9 cm on the roof plane (Check Distance between panels on roof installation for further information).

The configuration of the solar panels will be two groups of 28 and 24 panels. The group of 28 panels connected in 7 strings connected in parallel, each string consists of 4 panels connected in series. The second group of 24 panels will be connected in 6 strings in parallel, each string made of 4 panels in series.

The strings of panels are firstly connected in series and then connected in parallel at the combiner boxes, one box for each group of panels, following the combiner boxes, where the protection elements are located. Each group of panels is connected from the combiner boxes to the charge regulators, in this case 2 charge controllers connected in parallel model **SmartSolar MPPT 250/85** from the company **Victron Electron**.

All the control elements such as the charge regulator, battery system and inverters are installed in a proper room. The connection lines between the different elements will be protected against over-currents and short-circuits by fuses and circuit breakers for the DC part as for the AC part. A distribution panel will be installed close to the inverter, from it different cables will emerge to the house and production area, under tube or another proper installation method.

A grounding system connects the neutral and masses of the solar panels, combiner boxes, wind turbine, turbine's regulator and charge regulators. For the DC part of the installation another grounding for the inverter and distribution panel masses and neutral will be suggested, so the differential protection in the house and production area can work in case of an isolation fault and to protect against indirect contacts. Circuit switch openers will be recommended to be installed at the combiner boxes of each group of panels so the panels can be disconnected for maintenance operation.

The solar panel system is expected to produce at least for 20 years, although the degradation rate is of 20 % normally within 20 years, the manufacturer states that the solar panels will still produce at **80 %** of its original performance for **30 years** in the future.

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Figure 23: Installation place of the solar panels. Source: Own

The battery system consists of 10 battery blocks, model **RESU 10** rated at **48 V** each block is from the company **LG Chem**. The configuration of the battery system is made by connecting the 10 batteries in parallel to supply the needed current capacity to the system.

The battery system could be either installed in the house's cellar or inside a small house close to the main house, where the actual diesel generator system is placed now. For this case study the location showed at Figure 24 will be the one suggested to install the battery system, charge regulators and inverters.

Figure 24: Possible install location for the battery system. Source: Own

The production of energy from the solar panels, wind turbine and the one, which comes from the battery system is DC[17], so inverters are needed to convert it to AC[18]. The chosen inverter

[17] DC: Direct Current
[18] AC: Alternating Current

is the model **Phoenix Inverter 48/5000** from the company **Victron Energy**. Two inverters are needed, connected in parallel.

The wind turbine has its own charge regulator for the battery system included within the price, model **RCE-ENAIR-120** with an elective working voltage of 24/48V. The charge controller has a series of 8 selectors that allow to choose the mentioned working voltage, the algorithm for the battery system, on and off position etc… The installation turbine's charge controller should be done in an interior location, as it is not suitable for corrosive environments, and it is vulnerable to water.

The wind turbine installation could be done either on the house roof or close to the house on a free standing tower or a guyed one. The height of the tower is important, because the higher it is, the more production will be achieved. The wind turbine's manual recommends to install it **10 m** higher, compared to the closest obstacle, and at a distance of double of that obstacle's height. Therefore a possible installation for the turbine could be on a tower, which is **15 m** tall and **10 meters** away from the house, as the house's height is around **5 m**.

The installation methods are only mentioned as a possible suggestion in this case study, as it was previously mentioned, we will not get into details regarding installation methodology.

An optional solar collector could be added to supply sanitary heated water for the house, its sizing feels out of the reach of this case study, so it will be only suggested.

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1.9. Impact of the project for the rural development

The previously exposed system composed of solar panels, wind turbine, electronics, connecting lines etc… has a positive and negative impact on the environment, which goes from its production time till its final expected life.

1.9.1. Environmental impact

Almost all the pollution/waste that solar panels produce comes from the raw material collection for its production and the construction itself.

Silicon is most commonly used in PV systems. The main process for solar panel production is the purification of the silicon to obtain the pure crystals. Solar panel manufacturing needs diffusion, oxidation and connects the steps, for which different amounts of chemicals are used. These chemicals are either disposed or recycled as much of them, as it is possible, and disposed in a controlled manner.[4]

So the PV panel production has very little impact on the environment, if the control process is correct, and the disposal of the different chemicals is done in a controlled manner.

Other elements of the off-grid system that could represent an environmental impact are: battery system, different electronics (inverter and charge regulator) and the different structures and materials such as: steel, copper.

The battery system is especially dangerous for the environment, due to its composing materials: sulphuric acid and lead. The acid has a risk of leakage and possible acidity of the ground, and since the lead is a heavy metal, it is toxic for the wildlife and the environment.

Therefore a correct maintenance of the battery system, and the proper disposal is critical in order to minimize its impact on the environment at the end of its life.

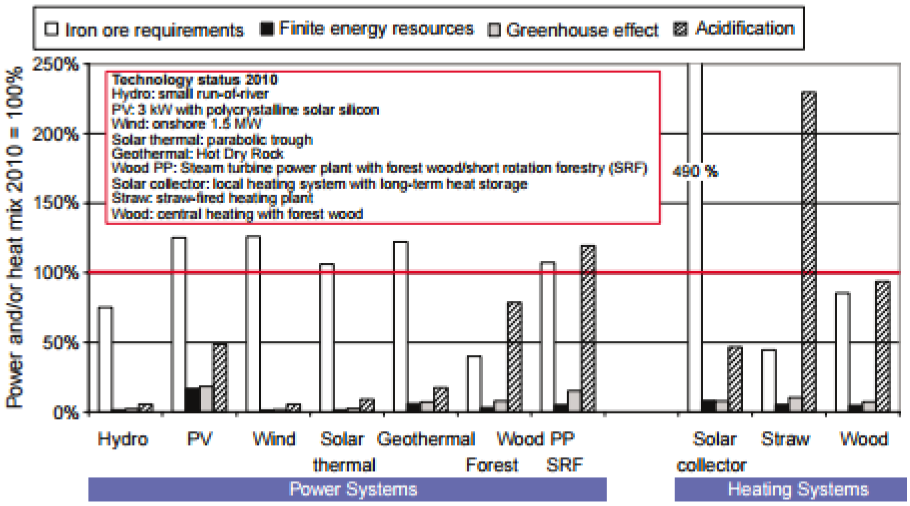

Figure 25: LCA for different renewable types of energy productions. Source:[18]

At Figure 25 we can see the different resources, GHG emissions and acidification from each renewable technology. We can see that wind and PV systems are almost identical, the PV GHG emissions and acidification are higher, mainly due to the chemicals and processes followed during the production of silicon crystals. The acidification will be higher for PV systems with battery system.

1.9.1.1. Land Use

The main disadvantage of solar panels is the large amount of land they use. Because of that commercial solar panels have low efficiency (Although it is improved almost every year). The main possible problem of land use in solar systems could be that they occupy agriculturally usable land. Big solar production plants need to choose carefully its place of installation, so the previously stated conflict does not exist.

In the case study it is not a problem, because the installation will be done on the roof, and not on a non-harvestable ground.

1.9.1.2. Water Use

Compared to other renewable energy production systems, photovoltaic panels do not require special amount of water for their production and operation.

1.9.1.3. Energy demand

For producing the main element of the off-grid system, the elements are the solar panels and the wind turbine. But because the installed solar power is much higher than the installed wind power, it can be neglected.

The energy needed for the production of solar panels (see Figure 25) is not really different from other renewable sources.

1.9.1.4. Visual impact

Although visual impact is a highly subjective question. In the case study the system is installed in a farm isolated from any nearby houses or population (the closest population is 5 km away).

Then no visual impact on any problematic area (the installation of solar panels can be restricted or forbidden on historic elements in cities). But in this case as it is a farm in the middle of the countryside, the visual impact feels to a subjective matter and every person will perceive the impact on a higher or lower manner.

The highest visible element is the wind turbine, which stands up on a **15 m** tower.

1.9.1.5. Noise impact

Solar panels do not make any noticeable noise during their normal operation. The main noise from the solar panels will come during their production and installation process (trucks etc…).

The wind turbine produces **48 db** noise during normal operation, which is lower than a conversational speech at **60 db** and is the same level as a working fridge.

So we can state, that the noise impact of the whole installation is almost negligible.

1.9.1.6. Air pollution and greenhouse gas emissions

The production of polycrystalline solar silicon panels causes green gas emissions of around **99 g CO_2/kWp**[18] and an on-shore wind turbine emits around **10.2 g CO_2/kWp** [18].

The **60%-70%** of the total gas emission of PV systems comes from the production, extraction, the manufacture of the module, installation and construction. From **21%-26%** of the total GHG emission comes from the power generation and maintenance, and between **5-20%** from the plant decommissioning and disposal.[19]

So we can see that most of the PV total GHG emission is from production, whereas for a typical coal powered generation plant **98%** of total GHG comes from coal mining, coal preparation, combustion, transport and power plant operation, with an average of **1000 g CO_2/kWh**[19]

Considering that the burning of diesel fuel emits around **10.21 Kg CO_2/gallon**[20],which is **2.69 Kg CO_2/Litre** in litres.

The total system production pollution is the following:

	kW.Installed (kW)	CO_2 g/kWp	Total.CO_2 g
Panels	17,68	99	1750,32
Turbine	3	10,2	30,6
		Total:	**1780,92**

Table 2: Total GHG emissions from the production of the renewable generators.

The operation of the renewable system will save a total amount of greenhouse emissions and avoids the use of the diesel generator. The use of the diesel generator emits GHG and different amounts of substances to the atmosphere. Then the GHG avoided will be the amount that the generator would have emitted in case it was still in use.

These are two possible scenarios:

	Yearly energy demand (Wh)	Generator (kW)	YearHours	Litres/h	LitresDiesel	DieselCO2	Total emission saved
0% use of the diesel generator	7798039,643	5000	1559,60793	6	9357,64757	2,69	25172,07197
25% use of the diesel generator	5848529,732	5000	1169,70595	6	7018,23568	2,69	18879,05398

Table 3: Total emission saved from the use of the hybrid system.

So we can see that the installation of the solar panels plus the wind turbine avoids the emission of **25,172 Tons** of CO_2 to the atmosphere in the best scenario, and **18,87 tons** for the a use of **25 %** of the total energy production from the diesel generator.

1.9.1.7. Ecosystem disturbance

The National Park of Ceahlău is 14 km far away, in proper distance to consider that neither the solar panels nor the wind turbine will have any influence on its ecosystem and wildlife.

The area where the farm is in a high area with few vegetation around, so the impact on the close wildlife is negligible.

The most possible disturbance will come from the wind turbine, since it is the highest object on the area, with birds in the area.

1.9.1.8. Recycling, waste production and management

The life expectancy for the usual PV system is of around 20-30 years. The life expectancy for the battery system is of around 10 years, with a needed change of around 2-3 times along the PV system's life. The expected life for the selected wind turbine is of 25 years.

The recycling and management of the wastes such as electronics (charge controllers, inverters), batteries and cable are fully developed and proven technologies.

Other possible waste such as the installation structure, materials such as steel, aluminium etc.. can be easily recycled based on well-developed methods such as re-casting etc…[4]

A good waste management politics for the battery system is expected to apply, to correctly manage its process.

Most of the installed solar panels around the planet are still in service at the moment, so common management policy for this type of waste has to be developed yet.

1.9.2. Social and rural impact

The area where the farm is located in Neamt county has one of the highest deprivation indicator in Romania, the construction of this index takes into account the unemployment rate, percentage of houses with electrical installation etc…[21] The employment rate for men and women for Neamt County is of 71,4% and 62,1%, respectively, with an average of 66,8% for both sexes for the year 2014. We can see a difference in unemployment between men and women, this gap aggravates the emigration of the women from the rural areas, due that they go to the cities to find better opportunities.

Romania also has one of the highest risk of poverty and social exclusion rates of the EU[19], only Bulgaria is behind, with a 37.3 % rate [22]. Neamt County has one of the lowest average monthly nominal salaries of all Romania with 1645 Lei beating only two other counties[23]. Then it is clear that the electrical safety supply and electricity production independence is a key factor that could help not only for this case study but could be also used for Neamt county

[19] European Union

region and employment that goes linked to the development of renewable technologies in the area.

The economy of Neamt county is mostly based on agriculture, sylviculture and animal breeding. The share of occupied population is pretty high, 46,84 % for agriculture, superior to the national level of around 29.48 %. [24] The north-east region (area where Neamt county is located) owns 14,47% of Romania’s agricultural and 18,26% of forest covered area.

Sylviculture has a high level of production in the area, considering that Neamt county has around 260.620 ha of forest. The north-east area supplies 28,28% of the total wood volume in Romania per year [24].

Examining the industry, the most active sectors in the area are:

- Machinery industry, engineering
- Food industry
- Wood, cellulose and paper manufacturing industry and furniture
- Light industry
- Tourism
- Medicines
- Transports

We can see that the area has a heavy dependency especially on the agriculture and sylviculture, as they represent almost the 50% of total employment in the area.

The area has a problem to keep the production since young population goes to urban areas and more than 28% of the population that stays there is over 60 years of age. From 1992 to 2011 Neamt County lost around 106.853 people, because of the emigration abroad or emigration inside Romania.[23]

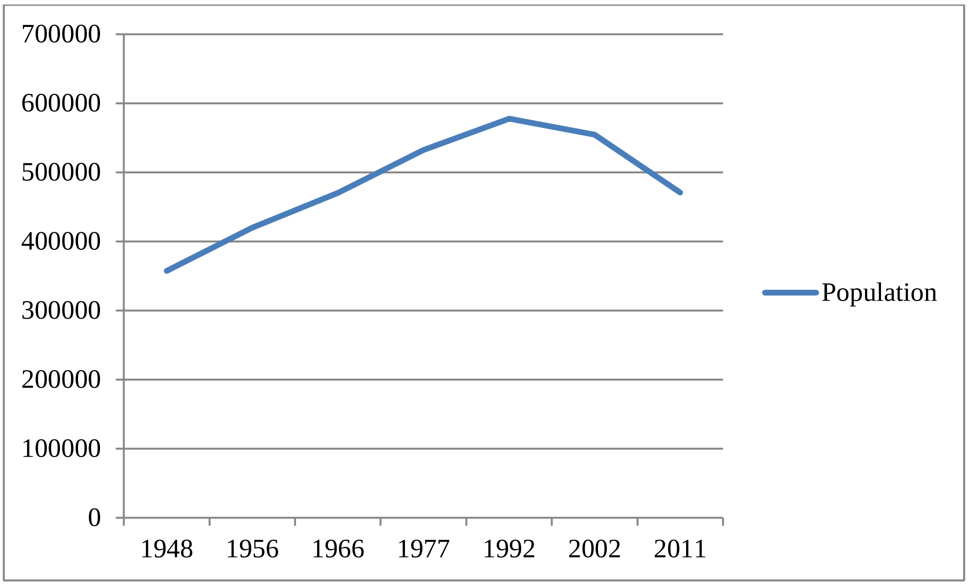

Figure 26: Population evolution in Neamt county. Source: INSSE

In addition, the natural growth is slowing down in the area, which means that more people die, than were born, 2656 people less were born in 2011 [23].

1.9.2.1. Energy security

Off-grid systems like the one described in this case study can guarantee the energy supply (as a backup or as a main source of supply) on areas where is difficult to provide energy supply, or it is expensive. The renewable systems can act as a backup for traditional system, where due to external factors there is a shortage of energy supply.

The farm examined in the case study initially had a problem with energy security, where the voltage that the generator could supply is lower than the nominal voltage of 230 V. The hybrid installation helps the energy security problem.

1.9.2.2. Rural electrification

The distributed generation of electrical energy that the renewable system can achieve could be the key solution to provide electricity to the few percentage of the population, because of a series of factors the conventional supply of electricity is not possible, difficult or too expensive. Because of its unique nature, renewable technologies can act as isolated points of production, what eliminates the problem to connect an isolated household by cable. In Romania around 45.5 % of its total population lives in rural areas in Romania. These kinds of technologies could be a perfect solution for these scenarios.

Renewable energy technologies also could help in rural areas as the ones we can find in Neamt County, acting as backup to traditional ways of energy producing and fomenting the increase of production. Examples could be the use of biomass related products that could come from the agriculture sector present in the region

1.9.3. Climate change mitigation

The system installed for the farm saves the atmosphere from around **25,17 tons** of CO2 every year, as we have seen previously. The energy production generates around **29%** of total GHG emissions in the US, for example [25]

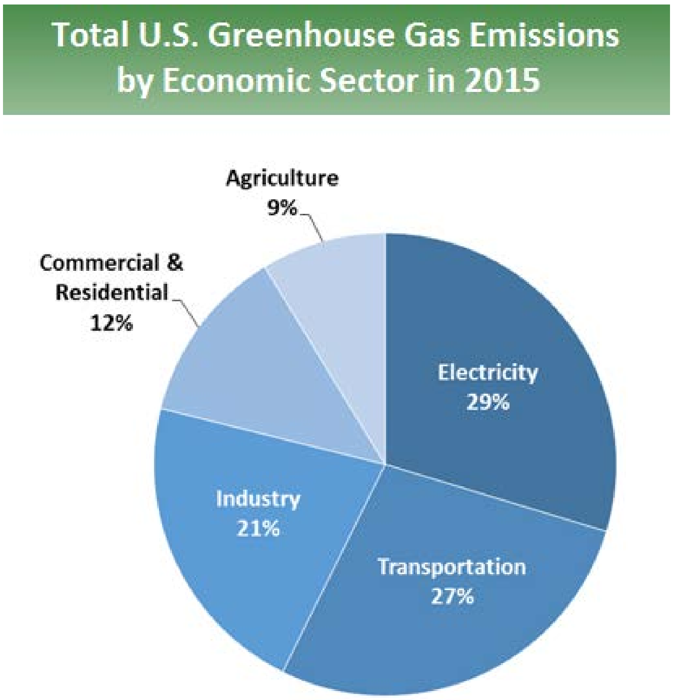

Figure 27: Origin of the GHG by source in the USA. Source: EPA

Also the losses due to the transportation of the electricity are around **21.5%** in Europe [13], this is mainly due to the long distance of transportation and losses due to heat loses etc…

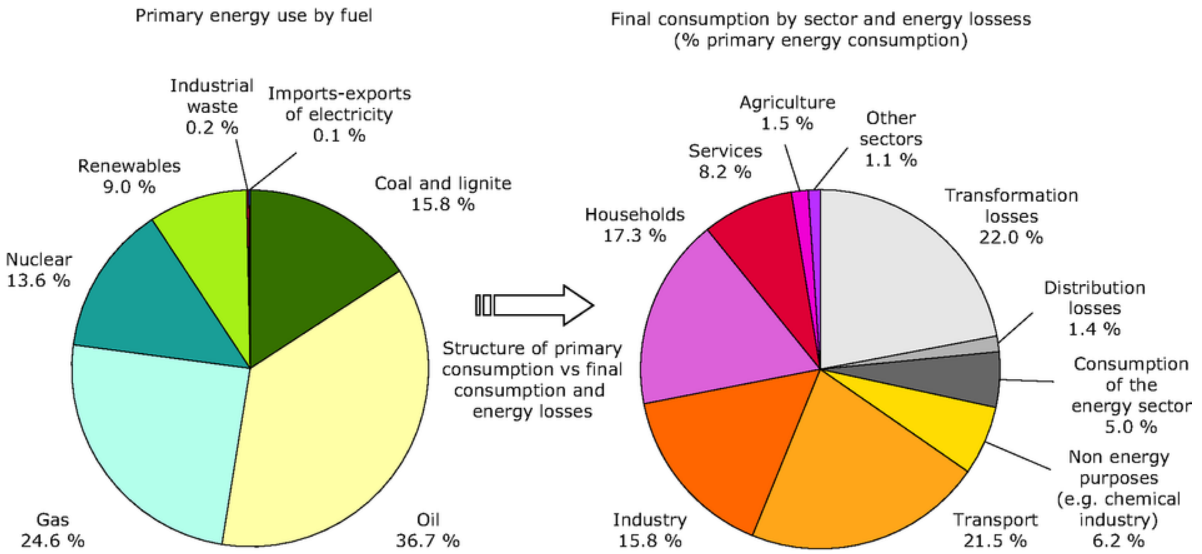

Figure 28: Primary consumption vs final consumption and energy loses. Source: EEA

Therefore renewable distributed supply can help the both previously mentioned statements. A distributed supply does not have the same loss issues as a centralized traditional supplier.

Traditional production power plant also works with oil, gas and coal, that emits a huge amount of GHG to the atmosphere (see Figure 27)

1.9.4. New jobs and business opportunities

The renewable market generates more employment directly and indirectly as well, than traditional centralized power supply, because of more amount of production points and because the systems need maintenance, too.

Therefore, different kinds of employment levels are generated:

- **Direct:** employment from the engineers etc.. who work on the development, and sizing of the installation. Personnel for the construction and installation of the system and qualified personnel for the maintenance etc…
- **Indirect:** Manufacturers of the components of the installation, distributors of the pieces and components. Possible new workers on the farm due to the savings from the installation that allow to increase the working force.

So the spread of these kinds of technologies around the area could promote the creation of more work places around the area and even around the country.

Possible bigger territorial involvement with bigger renewable projects, as for example the installation of a cogeneration plant fuelled by biomass or the installation of a community solar panel system that generates power for the whole village, could mean the creation of much more job positions not only in the village, but in the whole county. These changes could mean the improvement of the social situation and the possible improvement of life quality and a more stable population.

1.10. Conclusions

Here come the conclusions and the summing up of the case study. The farm had a lot of energy needs, but due to its difficult geographical location, the normal way of energy supply was not possible, especially from economical aspects.

The solution design in this project can provide more than enough energy production and most importantly **security** of the energy supply thanks to the installation of the wind turbine backup as a battery charging supporter. The use of only renewable solution is a strength on ecologic way of thinking, with the avoidance of **GHG emissions** on operation and the end of the dependence on the traditional supply power plants.

But the most important strength on this project solution is, that it is a complete solution that fully satisfies the client's needs.

Weaknesses of the project are, that the amount of panels needed is quite large, and the initial investment is quite high, with a late payback of the investment. Other weakness could be that there are much more equipment for the balance of the system, the maintenance will be much tedious than a simpler solution's (a bigger diesel generator for example) and more expensive **O&M**.

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Calculations and annexes

Calculations and design ;

2. General information

The farm produces dairy products. It is divided into two parts: a working area on the left Figure 28 and a house on the right (green roof).

As mentioned before the farm is 5 kilometers far away from Călugăreni’s terms (Neamt county, Romania).

Figure 29: General overview of the farm

Location: Bacâu, Neamt County (Romania)

Coordinates: 47°04'19.2"N 25°56'06.1"East

Elevation: 864 m above sea level

The energy what the farm requires can be divided into two parts: Electrical and Heat needs.

The production part of the farm is used the whole week, while the house is kept for use during weekends by the owner. We see that two clearly different parts exist, the production area of the farm, and the house itself.

The method for sizing the installation, will be choosing for the least favorable month, this means the month when the solar irradiation is the lowest throughout the year.

2.1. Sizing process guideline

Before jumping right into the calculation process, a guide will be established in order to make easier to follow the whole process.

The process for sizing the installation will be as follows:

1. **Calculating the power needed for the installation**
2. **Measuring the wind and sun resources**
3. **Small wind turbine sizing**
4. **Photovoltaic installation sizing**
5. **Sizing of the battery system**
6. **Inverter and regulator**
7. **Connection lines between elements**
8. **Protections**
9. **Others**

The exact reasons why certain elements were chosen etc… has been exposed on previous chapters of this case study, so in case of doubt about some of the aspects about to be exposed check part 1.5 and 1.6, where the reasons are deeply explained.

Calculations also will be included in this section, such as emissions to the atmosphere saved thanks to the installation. The distance needed between the solar panels, the selection of the type of solar panel etc..

2.2. Power needs of the installation

The installation consumptions can be divided into two parts: Consumptions related to production and consumptions related to the house. All consumptions of the farm are considered to be AC.

The production part consumes the most; it has two elements, an electrical boiler and a refrigeration device. The boiler is used along the year used for the production of dairy products, boiling milk and other elements for the elaboration of different products. The fridge is in continuous use to preserve the dairy products.

- **Electrical boiler:** Power: 2000W
- **Industrial fridge**: Power: 750W

On the other part, the house has a basic electrification degree. It has the following elements:

- **Fridge**: Power: 150W
- **Cleaning machine**: Power: 1000W

- **Electrical stove**: Power: 2000W
- **Lights**: Power: 40W Amount: 20
- **Power sockets**: Power: 3450W Amount: 10
- **Water pump**: Power: ½ CV≈367,5W

Also the house has heating system which is used in winter during the three coldest months.

Now that we have the power needs we will need now the Wh/day that the installation consumes every day. This is needed for the sizing of the power generation system. A series of factors will be used, so the installation is not oversized, these factors are taken from the Spanish regulation ITC-BT-25 [26]

For the amount of hours of use for each element a combination of collected data from the owner, studies of use [27][28] and own consideration has been followed.

We know the **boiler** is used all around the year for a total of **2100h/year**. The rest of the elements need to be studied in order to determine the amount of hours they are used.

- **Fridge and Industrial fridge:** Around 8 hours every day. And they work 7 days/week
- **Cleaning machine:** Considering that the house is used on weekends. 1 hour/day and 2 days/week of use.
- **Electrical stove:** 2 hours of use a day for 2 days/week
- **Lights:** 6 hours of use during the low light parts of the day
- **Power sockets:** A maximum of 2 hours a days for the weekend
- **Water pump:** 3 hours of use per day.

Let's take a look then at Table 4 to see all the previously mentioned information together.

	Power (W)	Hours	F.Simult	F.Use	Days/week	Weeks/year	Wh/year:	Wh/day
Boiler	2000	5,753424			7	52,1428571	4199999,52	11506,848
Ind.Fridge	750	8			7	52,1428571	2190000	6000
C.machine	1000	1			2	52,1428571	104285,714	285,714286
Elec.Stove	2000	2	1	0,75	2	52,1428571	312857,143	857,142857
Fridge	150	8	1	1	7	52,1428571	438000	1200
Lights	800	6	0,3	0,75	2	52,1428571	112628,571	308,571429
Wat.Pump	367,5	3	1	0,7	2	52,1428571	80482,5	220,5
Sockets	34500	2	0,2	0,25	2	52,1428571	359785,714	985,714286
						Total:	7798039,16	21364,4909

Table 4: Power consumed by the farm daily

We can see at the upper table the factors we previously mentioned, let's define them, for the better understanding, what they are used for:

- **Factor of simultaneity:** It represents, of all the total elements of the same type, for example the 20 lights, the amount of them that on a normal use can be simultaneously connected. For example for the 20 lights applying the 0,3 factor we get that maximum around 6 lights are connected at the same time
- **Factor of use:** This factor states the percentage of the total power used on a normal basis.[26]

Note that for the Lights and the Sockets the power has been multiplied by the total amount of plugs and light points to be present in the house.

In Table 4 can be seen what will be used in the following chapters for the sizing of the installation, the **total Wh/ year** in blue and the **total Wh/day** in orange. These are the values of the annual and daily energy requirements.

The power consumption from the production part (**Boiler+Ind.Fridge**) represents more than 75% of the all total consumption of the farm.

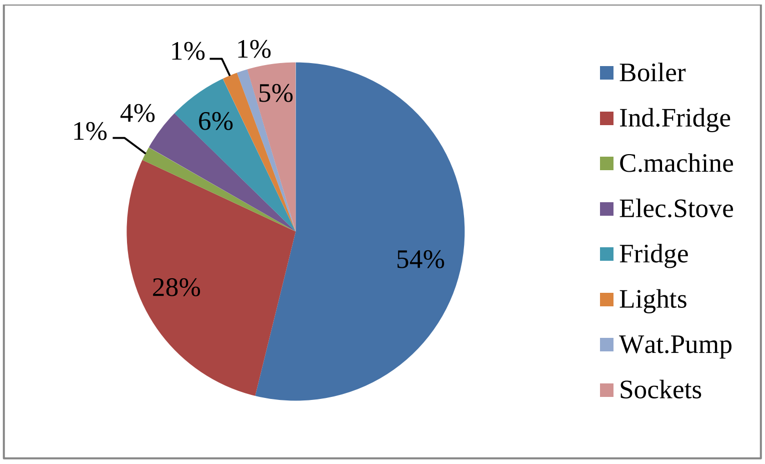


Figure 30: Daily consumption by the different elements

2.3. Measuring the sun and wind resource

Now we need to know the potential energy we can use from the sun and wind, so we can size the installation.

The sun resource is the most abundant energy resource on the earth [29]. Measuring the irradiation along the year on a certain area can be done through different databases available for the different countries and regions.

In this case study the free access database PVGIS financed by the European Union will be the one is used to estimate the solar resource available monthly for the location of the farm.

Monthly Solar Irradiation

PVGIS Estimates of long-term monthly averages

Location: 47°4'19" North, 25°56'6" East, Elevation: 864 m a.s.l.,

Solar radiation database used: PVGIS-CMSAF

Optimal inclination angle is: 36 degrees
Annual irradiation deficit due to shadowing (horizontal): 0.5 %

Month	H_h	H_{opt}	$H(50)$	I_{opt}	T_{24h}	N_{DD}
Jan	1210	1990	2140	64	-4.8	678
Feb	1910	2760	2880	56	-4.2	576
Mar	3370	4260	4290	45	0.5	499
Apr	4290	4740	4560	31	6.4	257
May	5310	5310	4920	18	12.1	124
Jun	5390	5130	4670	11	15.4	81
Jul	5650	5530	5070	15	17.5	65
Aug	4970	5350	5080	27	17.4	113
Sep	3620	4420	4400	41	12.8	226
Oct	2520	3670	3840	55	6.0	414
Nov	1500	2480	2680	64	2.7	572
Dec	1010	1750	1910	66	-2.5	699
Year	3410	3960	3870	36	6.6	4304

Figure 31: Monthly irradiation values. Source: PVGIS.

Hh: Irradiation on horizontal plane (Wh/m2/day)

Hopt: Irradiation on optimally inclined plane (Wh/m2/day)

H(50): Irradiation on plane at angle: 50deg. (Wh/m2/day)

Iopt: Optimal inclination (deg.)

T24h: 24 hour average of temperature (°C)

NDD: Number of heating degree-days (-)

We can see at Figure 30: Monthly irradiation values. Source: PVGIS.Figure 30 the different irradiation values for the different angles. The one we will use from this point will be the column of ***H(50)*** these are the amount of solar energy arriving at the installed angle of the installation: 50º

It can be seen that PVGIS itself suggests an optimal average angle to obtain the maximum output without changing the solar panels' angle. The reasons for choosing this angle have been already stated on previous chapters.

PVGIS also gives graphs representing the irradiation for the different angles we choose, see Figure 31. We can see that at 50º degrees we get a bit more of power at winter, which is the critical period where earth receives the least sunlight.

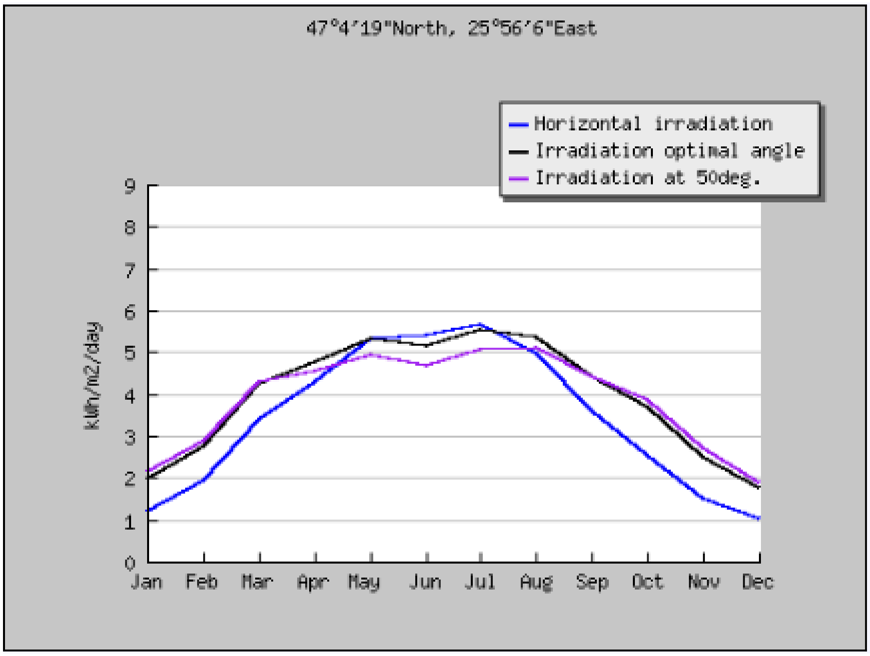


Figure 32: Irradiation along the year for the different angles. Source: PVGIS.

PVGIS gives a view of the obstacles and possible shadows that can occur along the year. The sun in winter hits the earth at a much sharper angle than in summer, this makes that the total amount of sun hours in winter is much less. Therefore, studying the losses due to possible objects blocking the solar panels from the sunlight is especially important in places like cities etc… In the case study the panels are situated high and facing south, so no losses due to shadows are considered.

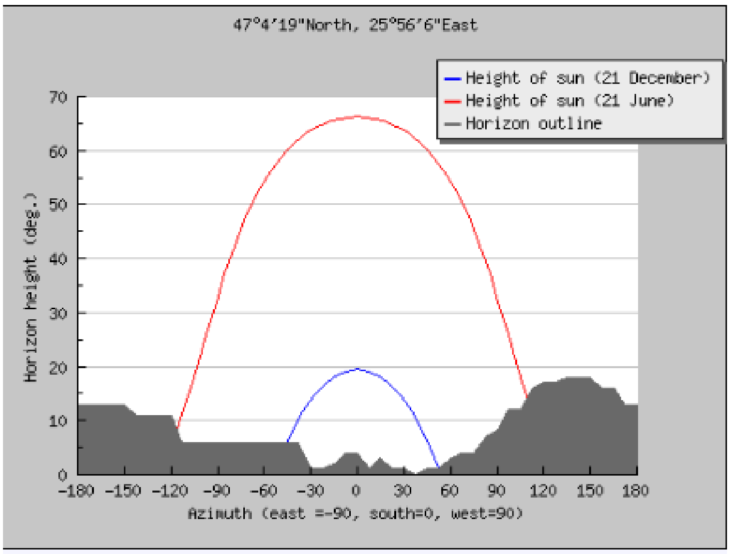


Figure 33: Yearly solar path. Source: PVGIS.

Wind resource availability on the other hand, is much harder to determine because it does not only change on a global level, but wind heats up at the equator and rises to move to one direction and goes to the opposite in colder regions, but also changes due to local geography (montains, valleys, sea present or not etc..).

All this makes wind a hard thing to quantify and more importantly predict. Although now every country more or less disposes of its own wind atlas, e.g. http://atlaseolico.idae.es/ for Spain. A deep study of the area is needed to measure the wind frequency and speed.

For measuring the power produce by the small wind turbine the speed of the wind and the amount of hours it blows are needed.

A rose of wind is a common graph that displays the speed of the wind, its direction and frequency (amount of hours). On Figure 33 we can see the rose wind for the village of Calugareni. It is noticed that wind blows mostly from South-West direction.

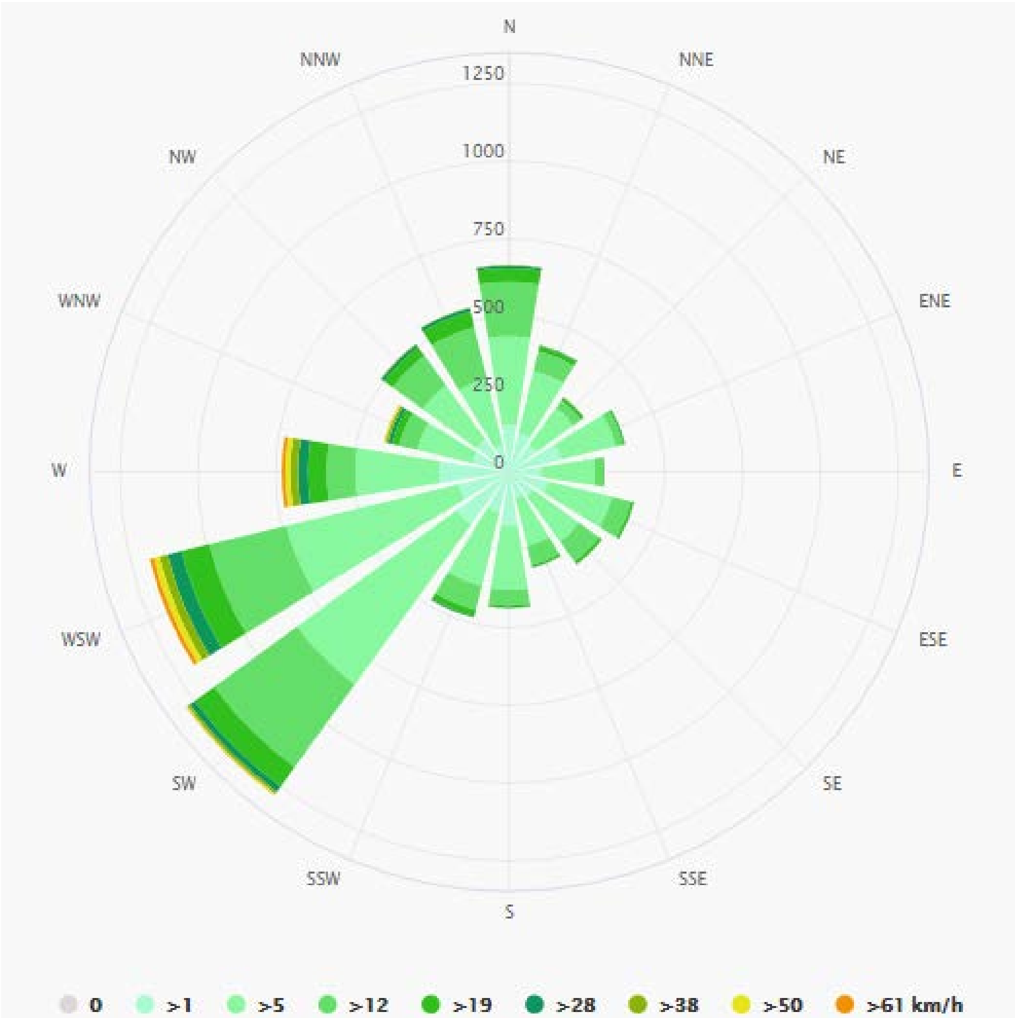


Figure 34: Rose of wind for Calugareni. Source: Meteoblue.

Compiling all data from the graph we get:

Spd (km/h)	Spd(m/s)	Hours/year
0	0	79
1	0,27777778	2147
5	1,38888889	4078
12	3,33333333	1677
19	5,27777778	471
28	7,77777778	162
38	10,5555556	79
50	13,8888889	44
61	16,9444444	26

Table 5: Wind speed and hours. Source: Own creation

The wind speed velocity mostly groups around the speed of 1,38 m/s, this means that most of the time the wind speed is quite low. Considering that a lot of small wind turbines have a cut-in-speed lower than that value, the speeds are not ideal.

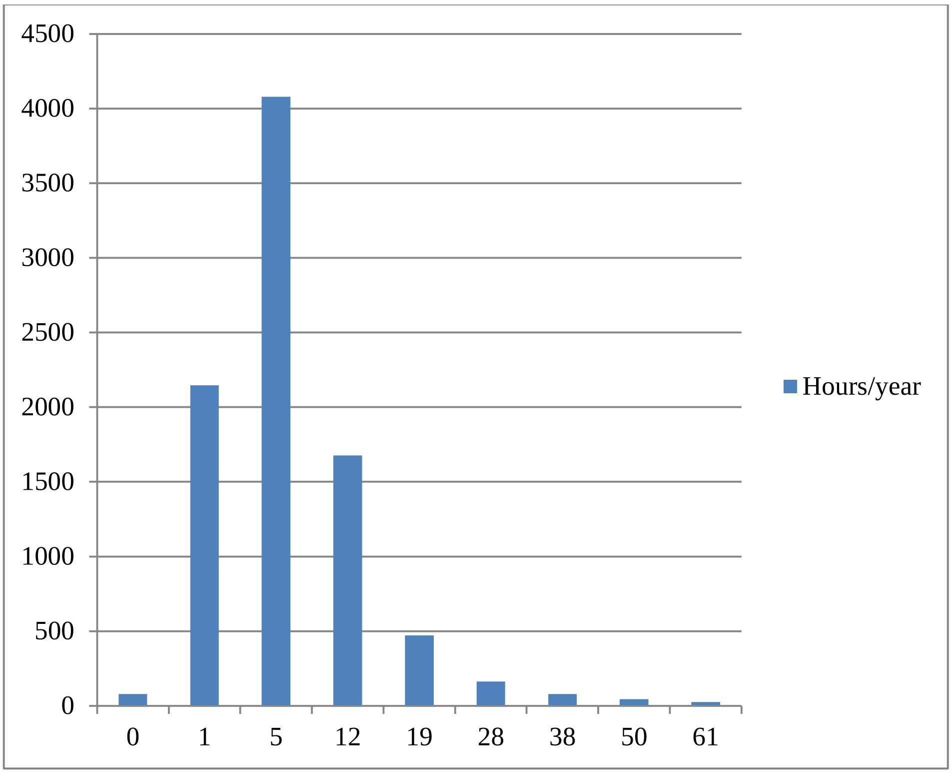


Figure 35: Hours/year vs speed of wind. Source: Own creation

Therefore, now we dispose all the tools needed to size the hybrid installation.

2.4. Small wind turbine sizing

The chosen small wind turbine is a E30 PRO by the Spanish company ENAIR. It has the following characteristics:

Number of blades	**3**
Power output	3000W
Working voltage	48V
Weight	125 kg
Swept area	11,34 m^2
Cut-in-speed	1,8 m/s
Nominal speed	11 m/s
Power control	Passive by centrifugal change of pass angle

Table 6: Small wind turbine characteristics

For further information about the small wind turbine check the annex.

So now let’s calculate the annual production of the wind turbine using the data provided by the manufacturer. Every turbine has a different Cp (power coefficient) that depends on a series of variables: tip speed ratio, the attack angle, number of blades, wind speed etc… So the manufacturer normally gives out those coefficients or directly gives the power production.

The equation for calculating the power produce by the turbine is:

$$Poutput = \frac{1}{2} * Cp * \rho * A * v^3 \qquad \textbf{(4)}$$

Cp: Power coefficient

P: Air density, at 15ºC is around 1,255 kg/m^3 at sea level

A: The area swept by the wind turbine

V: the speed of the wind

In this case the manufacturer gives the power generated at a certain speed directly. See Table 7, the yearly production and daily production from the wind turbine can be seen.

Average production could go higher or lower depending on different factors such as: Height at which the wind turbine is installed, wind change along the year etc…

			CUT-in-Speed: 1,8m/s		
Speed (km/h)	Speed(m/s)	Hours/year	Power	Wh/year	
0	0	79	0	0	
1	0,27777778	2147	0	0	
5	1,38888889	4078	0	0	
12	3,33333333	1677	180	301860	
19	5,27777778	471	300	141300	
28	7,77777778	162	1200	194400	
38	10,5555556	79	2000	158000	
50	13,8888889	44	2250	99000	
61	16,9444444	26	2500	65000	
			Total	959560	Wh/year
				2628,93151	Wh/day

Table 7: Power production of the turbine. Source: Own creation

Most of the production from the wind turbine comes due to low speed wind. As mentioned before by installing the wind turbine higher the power output is expected to go up.

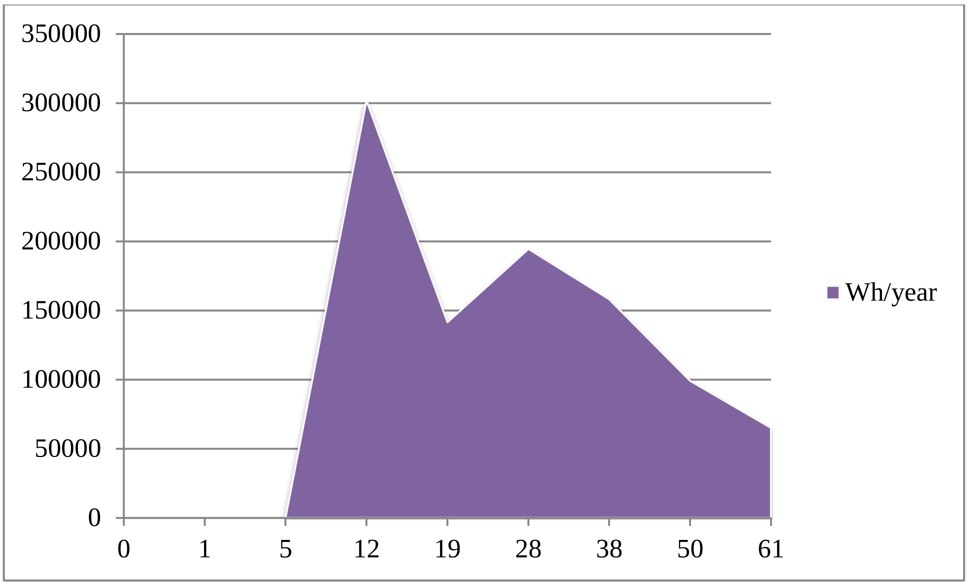


Figure 36: Production by wind speed

The power production achieved by the wind turbine will be taken from the daily energy needs from the farm, so we can size the photovoltaic installation on the next chapter correctly with no oversizing.

$$\boldsymbol{Pneeds = Pneedstotal - Pturbine = 21364{,}4909 - 2628{,}93151 = 18735{,}5607\ \mathrm{Wh}}$$

2.5. Photovoltaic installation sizing

For choosing the amount of panels for our photovoltaic power generation installation we need to calculate the minimum power to install, it takes into account the losses of all the systems and the least favorable month.[7]

The Performance rate (PR) takes into account all losses from the system. All elements composing the system have a performance rate, although it is usually high, the accumulation of losses from all the elements have a significant effect, especially on off-grid systems.

$$Pr = 1 - \left(Lossorient + Lossshade + Lossdirt + Losscable + (1 - Perfinv) + (1 - Perfreg + 1 - Perfbat)\right) \quad \textbf{(5)}$$

Where:

$\mathbf{Loss_{orient}}$: Losses due to orientation of the panels. In this case the panels face south, so it is considered 0.

$\mathbf{Loss_{Shade}}$: Losses due to other objects projecting a shadow over the panels. Considered 0 due to being on the roof and an open area (no nearby objects)

$\mathbf{Loss_{dirt}}$: Losses by dirt. It is considered to be around 5%.

$\mathbf{Loss_{cable}}$: Losses due to joule effect on the wiring. In this case they are considered to be around 5%

$\mathbf{Perf_{inv}}$: Performance of the inverter. For the chosen model it is 95%.

$\mathbf{Perf_{reg}}$: Performance of the charge regulator. For the chosen model it is 98%.

$\mathbf{Perf_{battery}}$: Performance of the battery system.

$$\boldsymbol{Perfbat = (1 - Kb) * (1 - \frac{Ka * N}{DOD})} \quad \textbf{(6)}$$

Where:

Kb: These are the losses while charging and discharging the battery system. It is considered about 5%.

Ka: Self-discharge value of the battery system. For the chosen stationary Li-ion type, the value is less than 7% every month, that is : $2{,}3 * \frac{10^{-3}}{\text{day}}$

N: Autonomy days of the battery system. For this installation 3 days are considered.

DOD: Maximum depth of discharging for the battery system. For this case study and the selected battery type the DOD is 90%.

$$Perfbat = (1 - 0{,}05) * \left(1 - \frac{2{,}3 * 10^{-3} * 3}{0{,}9}\right) = 0{,}942611$$

Putting all the data together we obtain the performance rate of the whole system:

$$PR = 1 - \big(0 + 0 + 0.05 + 0.05 + (1 - 0.95) + (1 - 0.98 + 1 - 0.942611)\big) = 0.7726$$

Now that we have the **PR** we can correct the power needed by the installation ("**Pneeds**" previously mentioned):

$$Pneeds_{pr} = \frac{Pneeds}{PR} = \frac{18735{,}56}{0{,}7726} = 24249{,}665\ Wh$$

In numerous bibliographies, a security factor is present [7]. This factor is used for safety reason to make sure that the demand is covered, it changes from source to source, in this case study the Security Factor (SC) is **1,1** which has been used.

Also, photovoltaic degrade over time, different technologies differ on degradation over time, also the location on the globe influence[30] a **1%/year** of production loss. So we need to oversize the installation, so in a **20-year**-period it will be still able to produce enough energy.

$$Pneeds_{PRSC} = Pneeds_{PR} * Factor_{degrad} * Factor_{security} \quad (7)$$

Where:

Factor$_{degrad}$: There is a 20% of loss over 20 years. The factor will be 1,2.

Factor$_{security}$: It is 1,1.

$$Pneeds_{PRSC} = 24249{,}665 \ * 1.2 * 11 = 32009{,}558\ Wh$$

The panel chosen is a monocrystalline solar panel, model **TM-M672320/340** from the company **Tamesol**. The characteristics of the panel are the following:

Maximum Power at STC:	**340 W**
Optimum Operation Voltage (Vmp):	37.76 V
Optimum Operating Current (Imp):	9.00 A
Open Circuit Voltage (Voc):	46.80 V
Short Circuit Current (Isc):	9.46 A
Module Efficiency:	17.51 %

Table 8: Solar panel characteristics.

Solar irradation changes along the day, a common concept is used in photovoltaics, that is Peak Sun Hours (PHS). PHS is the amount of hours of **1000 W/m^2** irradiation received on a day. It is used to calculate the minimum power to install

$$Pinstall = \frac{Pneeds_{PRSC}}{PSH_{month}} \quad \textbf{(8)}$$

The PSH what we will take is from the least favorable month, which is December (see Figure 30). The irradiation values are from the **H(50)**, due to the fact, that that is the angle of installation.

$\mathbf{PSH_{December}}$: 1,910 kW/m^2

$$Pinstall = \frac{Pneeds_{PRSC}}{PSH_{december}} = \frac{32{,}009\ Kwh}{1{,}910\ \frac{Kw}{m^2}} = 16{,}7586Kw$$

Now the amount we need, considering the maximum power output for the panels is 340W.

$$Number_{panels} = \frac{Pinstall}{Power\_panel} = \frac{16758\ W}{340\ W} = 49{,}29\ panels \approx 50\ panels$$

We chose the closest higher integer from the previous equation is the amount of panels to install of the photovoltaic installation.

To make easier the installation process we will augment the number of panels to 52. More information in the following **chapter 3.1.**

2.6. Sizing of the battery system

Since the system is off-grid, as we already mentioned previously, we will need an energy store system to accumulate the excess energy.

The battery system will work at 48 V to reduce the amount of losses and lowering the current (less joule effect losses due to lower current) due to the higher voltage, to be able to install thinner cables.

The equation to calculate the amounts of Ah needed is:

$$Cbatsystem = \frac{1{,}1*N*Id}{DOD*Per_{BatInvReg}} \quad \mathbf{(9)}$$

Where:

Cbatsystem: It is the capacity needed to install in Ah

N: It is the autonomy of the battery system. Considered to be 3 days.

Id: It is the daily need from the power consumption of the farm

$$Id\colon \frac{Pneedstotal}{48\ V} = \frac{21364.69\ Wh}{48\ V} = 445{,}09\ Ah$$

DOD: It is the depth of discharge. In this case study it is considered to be 0,9.

$\mathrm{Perf}_{\mathrm{BatInvReg}}$: It is the combined performance of the battery system, regulator and inverter.

$$Perf_{BatInvReg} = \mathrm{Perf_{Bat}} * \mathrm{Perf_{Inv}} * \mathrm{Perf_{Reg}} = 0.942611 * 0.95 * 0.98 = 0.877570$$

Then:

$$Cbatsystem = \frac{1.1 * 3 * 445.09}{0.9 * 0.87757} = 1859{,}6769\ Ah$$

The chosen battery is the model Resu 10, from the company LG Chem. It is a deep cycle Li-ion battery, a block type battery of 48 V rated voltage per module.

Since the autonomy of the system is expected to be of around 3 days, we can consider a discharge rate of 72 hours for the battery system. The lower we discharge the battery system the higher is the capacity.

Weight (kg)	75
Total energy (kWh)	9,8
Capacity (Ah)	189
Voltage Range (V)	42-58,8
Max Power (kW) for 3 sec	7

Table 9: Characteristics of the LG Resu 10 battery

For the Resu 10 model the capacity for a 1C discharge is :

Cbattery =189 Ah

Then the number of batteries in parallel needed will be:

$$Number_{BatteriesParallel} = \frac{Cbatsystem}{Cbattery} = \frac{1859.67 \text{ Ah}}{189 \text{ Ah}} = 9.839 \approx 10 \text{ batteries}$$

Choosing the inverter and charge regulator:

2.7. Charge regulator

The charge regulator and inverter are from the company **Victron Energy**.

Let's begin choosing the charge regulator. The parameters that will define the amount of the regulators we will have to install will depend on the characteristics of the solar panels we chose (the wind turbine has its own regulator).

The parameters we will use from the solar panels are (see Table 8) :

Vosc: The open circuit voltage from the solar panels, Vosc=46.80 V.

Isc: It is the solar panel's short-circuit current. It is the maximum current that on normal operation, the solar panel could give. The value in the table is: Isc= 9.46 A

Victron Energy provides a group of solar charge regulators that can be connected at 12,24,36 and 48 V. The ones we will discuss are the **SmartSolar MPPT 150/85**, **150/100**, **250/85** and **250/100**. The first number stands for the maximum PV open circuit voltage and the second one the rated current of the regulator, e.g 150 V and 85 A.

Then:

$$Voltage_{safety} = Factor_{security} * Vosc \quad \textbf{(10)}$$

$$Current_{safety} = Factor_{security} * Isc \quad \textbf{(11)}$$

Factor$_{security}$: Is a security parameter to be sure we protect the regulator. The factor is normally defined as a 25% increment over the normal value[7]

$$Number_{PanelsSeries} = \frac{Voltage_{Reg}}{Voltage_{safety}} \quad \textbf{(12)}$$

$$\boldsymbol{Number_{PanelsParallel} = \frac{Current_{Reg}}{Current_{safety}}} \quad \textbf{(13)}$$

Therefore applying all this data we get the maximum number amount of panels we can connect in series and parallel for the values of the charge regulators.

Voltage	Max.Num.Panels.Serie	Num.Panel.Serie
250	4,273504274	4
150	2,564102564	2
Current	**Max.Num.Panels.Parall**	**Num.Panel.Parallel**
85	7,188160677	7
100	8,456659619	8

Table 10: Maximum number of panels series and parallel

We have 50 panels to install, thus we know the amount of charge regulators we will need for every model:

$$Number_{Regulators} = \frac{50 \quad Panels}{Num.Panel_{Serie} * Num.Panel_{Parallel}} \quad \textbf{(14)}$$

Applying the upper equation we get the panels we will need:

Model	Num.Panel.Regulator	Num.Inverters
150/85	14	4
150/100	16	3
250/85	28	2
250/100	32	2

Table 11: Number of charge regulators

Looking at Table 11, we see that the models 250/85 and 250/100 are the ones that allow us to use the less amount of inverters, then we will choose the model 250/85 (cheaper than 250/100) and we will need two of them.

Although the amount of panels needed is 50, the final number will be 52. This is to easier the installation process and adapting to the chosen charge regulators. Dividing the panels in two groups of 25 panels each one is not compatible, neither in groups of 26+24, 27+23 and 28+22, therefore the amount of panels is increased by two leaving it at a total amount of 52.

The connection scheme for the panels will be 28+24. One group of 28 panels and 24 panels are connected to a charge regulator. The regulators are connected in parallel to the battery system.

SmartSolar Charge Controller 250/85	
Battery Voltage	12/24/48 V
Rated charge current	85 A
Maximum PV open circuit voltage	250 V
Maximum efficiency	99%

Table 12: Charge regulator operative characteristics

2.8. Inverter sizing

For the election of the inverter, we need to know the power that can be simultaneously connected from the consumption side. In order not to over-size the election of the amount of inverters needed, there is a criterion for considering how high the simultaneously connected power can be:

Boiler	2000W
Fridge + Industrial Fridge	900 W
Electrical Stove	2000 W
Cleaning machine	1000W
Power socket	3450 W* 0.5=1725 W
Lights	800 W*0.3*0.75=180W
Total Simultaneous power:	**7805 W**

Table 13: Simultaneous connected power

The factors applied are:

- **Power sockets**: A factor of use of 50% percent of the total power capability of the socket for one socket is considered. The unlikely scenario of all the consumptions connected at the same time justifies the application of this factor

- **Lights**: A factor of simultaneity of 30% for all the lights is applied. And a factor of use of 75% for power use for the lights.

$$Power_{SimultaneousSEC} = Power_{Simultaneous} * Factor_{Security} \quad \textbf{(15)}$$

Factor$_{\textbf{Security}}$: is the same coefficient previously used for the charge regulator election, is a factor of 1.25 to secure the safety operation of the inverter.

$$Power_{SimultaneousSEC} = 7805\ W * 1.25 = 9756.25\ W$$

The inverter is also from the company **Victron Energy**, the one chosen is the model **Phoenix 48/5000**. Works at 48 V from the battery side and has a power output at 25ºC of 5000VA. The output is a sinusoidal wave of 230 V to feed the consumptions.

$$Number_{Inverters} = \frac{Power_{SimultaneousSEC}}{Power_{inverter}} = \frac{9756.25}{5000} = 1.95125 \approx 2\ Inverters$$

As the simultaneous connected power can be very high, we chose the biggest inverter **Victron Energy**, it is the one that allows us to only use two of them, with the rest we will need more than 2 inverters.

Connection between lines:

The connection cables that will be defined in this section will be the following ones:

- Solar panels-Combiner box
- Combiner box-Charge regulator
- Charge regulator-Battery system
- Battery system- Inverter
- Inverter- Consumption

Cables for the wind turbine:

- Wind turbine- turbine charge regulator
- Turbine charge regulator- Battery system

To size the connection between the different elements, the maximum current that could flow through the conductor (it means if the conductor is physically able to conduct the current without burning) and the voltage drop along the line will be taken into account.

The cables used for this sizing are the ones from the **Prysmian**'s catalog for photovoltaic installation, **TECSUN (PV) PV1-F.** The catalog disposes of a series of colors: Red, blue and black. The insulation cover of the cables is **HEPR 120° C**, cables at a rated voltage of **0.6/1 kv.**

The color helps with the installation process, red and blue will be used for the positive and negative on the solar panels strings respectively, for the rest of the installation red and black cables will be used for positive and negative.

The suggested installation method for all cables will be on a tube with two pairs of cables inside, named installation **type B1** for the outside line and **type F** for inside ones by the Spanish norm **UNE 20460–5–523** [31]. These methods are just suggested and not definitive, it is used to give a better and more real view on how the installation will behave. Maximum tolerated current for each cable section will be taken from the **table A.52-1 bis** which is from the previous normative.

The equations used to calculate the cable section needed in function of the voltage drop is the following:

For single-phase and direct current:

$$S\ (mm) = \frac{2*L*I}{c*(V_a - V_b)} \quad \textbf{(16)}$$

For single-phase and alternating current:

$$S(mm) = \frac{2*L*P}{c*e*V^2} \quad \textbf{(17)}$$

- **L**: the length of the conductor itself in meters.

- **I**: the current circulating through the cable in Ampers.
- **P**: the power transported on the line in Watts.
- **C**: electrical conductance of copper. At 20º C being 56 m/Ω*mm^2
- **Va**: the voltage at the beginning point of the conductor in Volts.
- **Vb**: the voltage at the end of the conductor in Volts.
- **E**: the voltage drop of the line, is a non-dimensional parameter.
- **V**: the voltage at the alternating current line between a phase and the neutral, which is 230 V.

The maximums and recommended voltage drops used in this case study are the ones considered in the Spanish legislation (IDAE) [32]

Voltage drop (%)	Allowed value (REBT)	Recommended Value
Solar panels-Charge regulator/Inverter	3 %	1%
Charge regulator-Battery system	1%	0.5%
Battery system-Inverter	1 %	1%
Inverter-Light points	3%	3%
Inverter- Appliances	5%	3%

Table 14: Voltage drop values. Source: IDAE

First, let’s start the selection of the proper conductors for the DC[20] part of the installation, which starts from the solar panels and ends at the inverter:

- **DC part of the installation:**

Line Panels-Combiner box and line from combiner box-Regulator:

The selectivity of the cables for the panel-combiner box and the junction box-regulator will be so the total voltage drop of both lines is within the range of the ones stablished in Table 14.

$$Voltage\ drop_{PanelRegulator} = Voltage\ drop_{PanelCombiner} + Voltage\ drop_{CombinerboxRegulator} < 1\% = 0.01 \quad \textbf{(18)}$$

The section of the conductor for the Solar panel-Combiner line will depend mostly on the distance from the positive pole of the panel to the combiner as all panels are arranged in strings of the same amount of panels 4

The minimum conductor’s width will be of **6 mm^2** on the DC to lower the voltage drop on that part because the voltage lowers the losses, which are higher due to joule effect (higher current). On the other hand, the installation process is easier.

[20] Direct current

Voltage drop of the string-panels to combiner						
N.Strings	Distance (m)		Cable width (mm)	Current string (A)	Voltage drop (%)	
	minimum	maximum				
1	1	5	6	9	0,00035468	0,00177342
1	5	9	6	9	0,00177342	0,00319215
1	9	13	6	9	0,00319215	0,00461089
1	3,53	7,53	6	9	0,00125203	0,00267077
1	7,53	11,53	6	9	0,00267077	0,0040895
1	11,53	15,53	6	9	0,0040895	0,00550824
1	1	5	6	9	0,00035468	0,00177342
1	5	9	6	9	0,00177342	0,00319215
1	9	13	6	9	0,00319215	0,00461089
1	3,53	7,53	6	9	0,00125203	0,00267077
1	7,53	11,53	6	9	0,00267077	0,0040895
2	11,53	15,53	6	9	0,0040895	0,00550824

Table 15: Voltage drop at solar strings. Source: Own.

In Table 15 we can see the voltage drops for the different strings. The red color symbolizes the positive cable of each string and the blue one the negative one. The length of every cable changes depending on the string position on the roof.

Considering that the combiner box for each group of panels will be installed at a maximum distance of **1 m** (the closest possibly). The distances between the negative (blue) and positive (red) will be of **4 m** which is the width of 4 panels in series:

$$Distance_{NegativePositive} = Width_{panel} * 4 \quad \textbf{(19)}$$

Width panel: Taken from the manufacturer datasheet **0.996** m

$$Distance_{NegativePositive} = 0.996 * 4 = 3.984\ m \approx 4\ m$$

The distance between superior lines of panels will be the minimum distance of 1 m plus the minimum distance we will need to leave to avoid shadowing (check **Distance between panels on roof installation** for more information)

$$Distance_{UpperPanels} = MinimumDistance + Distance_{AvoidShadowing} \quad \textbf{(20)}$$

Minimum distance: The distance to the group's combiner. The minimum distance is **1** m.

Distance$_{\textbf{AvoidShadowing}}$: The distance to avoid shadowing. Calculated as **2.53** m.

$$Distance_{UpperPanels} = 1 + 2.53 = 3.53\ m$$

The current is the highest one on normal use, that is the **Impp** (current at maximum output at STC[21]) of the solar panel (check annex for **TM-M672320** datasheet)

Now it is needed to check that the selected diameter of cable is able to support the short-circuit of the string, that will be the maximum current that can be tolerated on normal operation process.

Cable section (mm^2)	Maximum tolerated current for under tube installation (A)*	Maximum expected current (A)
6	46	9.62

Table 16: Thermic criterion for the selected cables. Source: Own

*The maximum tolerated current of the conductor is the one considered for an under tube installation for the selected sections (type B1 installation taken from table 52-B1/A.52-1 bis 40º C, insulator XLPE 2[31]**)**.

Now let's see the line Combiner box-Regulator:

	Cables combiner to regulator				
Group	Lenght (m)	Current (A)	Conductor mm	Volt.drop	V.drop Panel-Combiner
1	12	54	35	0,00437781	0,009886049
2	12	63	35	0,00510745	0,010615684

Table 17: Voltage drop from the combiners to the charge regulators. Source: Own

Considering that the Combiner box is installed at a maximum of **1 m** away from both groups of the panels. We obtain at **Table 17** the voltage drop on the line and the sum of voltage drop from the panels (the worst scenario, when the string is with the highest voltage drop) to the junction box.

Thermic criterion for the combiner box-regulator line:

Group	Nominal current (A)	Conductor (mm)	Maximum tolerated current (A)*
1	54	35	137
2	63	35	137

Table 18: Maximum current for the line combine-regulator

*Current corrected for the suggested installation method **B1**.

[21] Standard Conditions

We can see that the chosen section is able to withstand the nominal operation of the line.

Being the total voltage drop for the compound line solar panel-regulator, the sum of the line with the highest voltage drop, plus the voltage drop for the cable from the combiner to the charge regulator.

Where:

$$\text{Voltage drop}_{\text{PanelRegulator}} = \text{Voltage drop}_{\text{PanelCombiner}} + \text{Voltage drop}_{\text{CombinerboxRegulator}} < 1\% = \mathbf{0.01} \quad \mathbf{(18)}$$

For **group 1** $Voltage\ drop_{PanelsToRegulator} = 0.00550824 + 0.004377 = 0{,}009886049$

For **group 2** $Voltage\ drop_{PanelsToRegulator} = 0.00550824 + 0.0051 = 0{,}010615684$

The voltage drop for the total line are within the ranges of **1%** as the recommended voltage drop. To easier the installation process all solar panels cables will be the same section, therefore all cables will be **6 mm^2** on the solar panels to combiner side. For the line from the combiner box to the charge regulator, the chosen section is **35 mm^2**.

	N.strings	Total cable lenght (m)	
Group 1	1	6	
	1	14	
	1	22	
	1	11,06	
	1	19,06	
	1	27,06	
Group 2	1	6	
	1	14	
	1	22	
	1	11,06	
	1	19,06	
	2	27,06	
		Total:	**225.42**

Table 19: Total meters needed for section 6 mm^2

Group	Total cable lenght (m)
1	12* 2 cables
2	12* 2 cables
	Total: **48**

Table 20: Total meters needed for section 35 mm^2

Line charge regulator- battery system:

The highest power that the line connecting the charge regulators with the battery system will be the one coming from the solar panel system. The maximum PV[22] power output for 48V of the model **SmartSolar 250/85**, is 4900W (taken from the datasheet).

Therefore considering that there are 2 charge controllers in parallel the total maximum power coming from the PV to the battery system will be **9800 W**. Remind that the chosen system's voltage for the battery, regulator and inverter is **48 V**.

For each regulator line $Imax_{perRegulatorBattery} = \frac{4900\ W}{48\ V} = 102.08\ A$

Where the maximum distance is considered for the installation from the charge regulators to the battery system is **2 m**:

Cable regulator-battery				
Power (W)	**Lenght (m)**	**Current (A)**	**Section (mm)**	**Voltage drop**
4900	2	102,083333	35	0,004340278

Table 21: Voltage drop for the line connecting the charge regulator with the battery system. Source: Own

Let's check if the cable can withstand the current:

Nominal current (A)	Section (mm)	Maximum tolerated current (A)*
102.0833	35	174

Table 22: Maximum tolerated current for the line regulator-battery system

*For the installation method **F**.

[22] PV: Photovoltaic

We can see that the chosen section of **35 mm** is able to withstand the current.

The voltage drop at the connection regulator-battery is lower than the recommended value of **0.5%**. The selected conductor diameter is of **35 mm ^{2}**.

	Total cable length (m)
Connection charge regulator-battery system	2*2 pair of cables
	Total: **8**

Table 23: Total meters needed for section 35 mm^2

Line battery system to inverters:

The maximum power it will support is from the maximum simultaneous connected power from the power consumes (see Inverter sizing for more information about the criteria followed for calculating the maximum simultaneous connected power).

$$Power_{SimultaneousSEC} = 9756.25\ W$$

$$Imax_{BatteryInverter} = \frac{9756.25\ W}{48\ V} = 203.55\ A$$

The maximum recommend distance from the battery system to the inverters **2 m**.

Cable battery- Inverter				
Power (W)	**Lenght (m)**	**Current (A)**	**Section (mm)**	**Voltage drop**
9756,25	2	203,255208	35	0,008641803

Table 24: Voltage drop from battery system to inverters. Source: Own

The voltage drop falls right within the recommended value from Table 14.

But examining the thermic criteria for the cable we can see that it is not able to withstand the current that will pass through it, so we need to take a bigger cable section.

Nominal current (A)	Section (mm)	Maximum tolerated current (A)*
203.255	35	174

Table 25: Tolerated current for 35 mm cable cross section

*Type **F** installation

It can be clearly seen that the cable is not capable of handling the nominal current for the line. A new section of **70 mm** is chosen.

Section (mm)	Nominal current (A)	Maximum tolerated current (A)*
70	203.255	269

Table 26: New section maximum current values.

*Type **F** installation

The voltage drop for the new conductor line section is:

Cable battery- Inverter				
Power (W)	**Lenght (m)**	**Current (A)**	**Section (mm)**	**Voltage drop**
9756,25	2	203,255208	70	0,004320902

Table 27: Voltage drop for 70 mm section.

Where we can see that the voltage drop values are within the recommended ones, lower than **1 %**. Therefore the definitive cable section will be of **70 mm** for the battery-inverter line.

	Total lenght (m)	
Battery-Inverter	2* 2 cables	
	Total:	**4**

Table 28: Total length needed for 70 mm^2

- **AC part of the installation**:

Line Inverter to distribution panel:

The installation of distribution panel from where the two branches will emerge, one goes to the production area to feed the boiler and industrial fridge and the other one goes to feed the house consumptions. The distribution panel locates the protection of the lines, as well, and is located at a maximum of **1 m** from the inverter.

The section needed for the connection inverter will be the minimum that can support the current, considering that previously was stated that the minimum recommended section is of **6 mm**:

Power (W)	Nominal current (A)	Max tolerated current cable (A)*	Lenght (m)	Section (mm)	Volt. Drop
9756,25	42,41847826	46	1	6	0,00109779

Table 29: Line inverter to distribution panel. Source: Own

We can see that the section **6 mm²** is able to support the current, so there is no need to oversize it more.

Line distribution panel to consumption:

For this part two lines are needed to be sized:

- Line to the production area
- Line to the house

The maximum recommended voltage drop for both lines is **3%** of a phase-neutral voltage of **230V**. The distances to the production area and the house from the small house, where the inverters are located, is of **50 m** and **14 m** respectively.

The section takes into the account the previous data and the following formula is used $\mathrm{S(mm)} = \frac{2*L*P}{c*e*V^2}$ **(17)** :

For the production part:

$$S(mm) = \frac{2 * 50 \ * 2750}{56 * 0.03 * 230^2} = 3.094\ mm$$

Where:

P: The power of the boiler plus the industrial fridge, which is **2750 W**.

For the house part:

$$S(mm) = \frac{2 * 14 * 7006}{56 * 0.03 * 230^2} = 2.207\ mm$$

Where:

P: Is the power from the previously calculated maximum simultaneous connected power minus the power from the production part, that is: **P= 9756 W-2750 W= 7006 W**

At **TECSUN-PV-PV1-F** catalogue we can see that the closest cross sections are **4 mm** and **2.5 mm** respectively. But the selected diameter for both of them will be **6 mm** to make the installation process easier. Therefore the voltage drops we obtain are:

	Section (mm)	Voltage drop
House	6	0,011036941
Production	6	0,01547169

Table 30: Voltage drop on the consumes.

We can see that the voltage drops are well within the tolerated values for both cases. Lastly we need to see if the selected cables are able to withstand the maximum nominal current, considering that they are installed under tube (Type **B1** installation [31]):

Line	Section (mm)	Nominal current (A)	Maximum tolerated current (A)*
House	6	30.46	46
Production	6	11.956	46

Table 31: Maximum current for AC consume lines

*Type **B1** installation

We see in Table 31 that they are able to withstand it. Therefore the selected section will be **6 mm**.

	Length needed (m)
Inverter-Distribution	1
House	14
Production area	50
	Total: 65* 2 cables= 130

Table 32: Total length needed from distribution to consumption.

- **Wind turbine line sizing:**

The maximum power output from the wind turbine is maximum **3000W**, the working voltage of the turbine is of **48V.**

The allowed and recommended voltage drops for the wind turbine line connection are the same of that previously stated for the solar panel.

Line from wind turbine to charge regulator:

As we stated in the final solution description, the wind turbine should be installed around **10 m** away from the house, then considering that the charge regulator of the turbine will be installed where the other charge controllers are (the ones from the PV system) a total distance of **20 m** from the turbine to the regulator can be considered.

Wind turbine to Charge regulator					
Power (W)	Voltage	Current (A)	Section(mm)	Length (m)	Voltage drop
3000	48	62,5	95	20	0,0097901

Table 33: Voltage drop for the Wind turbine-Regulator line.

For a **95 mm** size cable the voltage drop is right within the recommended value, lower than **1%** total drop. Now let's see if the cable supports the nominal current along the cable:

Nominal current (A)	Maximum tolerated current (A)*
62.5	327

*Type **F** installation

It can be clearly seen that the cable is able to withstand the current.

Line from charge regulator of the wind turbine to battery system:

Where the voltage drop will be, considering that the charge controller is installed at a maximum of **2 m** from the battery system.

Charge regulator to battery system					
Power (W)	Voltage	Current (A)	Section(mm)	Length (m)	Voltage drop
3000	48	62,5	25	2	0,003720238

Table 34: Voltage drop from the regulator to the battery system.

The maximum tolerated current from the cable will be:

Nominal current (A)	Maximum tolerated current (A)*
62.5	140

Table 35: Tolerated current for the cable charge regulator of the turbine to the battery system.

The total amount needed of cable will be of:

	Length needed (m)	
Turbine-regulator	20	
	Total:	20*2 cables=40

Table 36: Total length needed of section 95 mm.

	Length needed (m)	
Turb.Regulator-Batt	2	
	Total:	2*2 cables=4

Table 37: Total length needed for section 25 mm.

Protections:

2.9. Fuses

The chosen fuses are **gPV** fuses by the company **SOCOMEC**, that is constructed according to **IEC 60269 standard**. With a rated breaking voltage of **1000 VDC** for the models from **1** to **600 A (**taken from the fuse datasheet**)**.

For the selection of the correct nominal current for the fuse it is needed to introduce the following equations:

For the protection of the cable system the fuse must meet the following criteria:

$$Ib \leq In \leq Iz \quad \textbf{(21)}$$

$$I_2 \leq 1.45 * Iz \quad \textbf{(22)}$$

Where:

Ib: The design current for the circuit

In: The the nominal current assigned to the protection device. Caliber.

Iz: The maximum tolerated current by the conductor.

I_2: The current where the activation of the device is guaranteed. For fuses made following the **IEC 60269** norm, the guaranteed activation current is **I_2=1.6*In**.

The short-circuit current along the lines must be calculated to see if the fuse device is able to protect against the short circuit currents:

$$Isc = \frac{Voltage\ at\ that\ line\ part}{\Sigma Resistances} \quad \textbf{(23)}$$

$$Breaking\ Capacity > Iscmax \quad \textbf{(24)}$$

$$Iscmin > Ia = I_{f5} \quad \textbf{(25)}$$

Where:

Iscmax: The maximum short-circuit current expected on the line.

Iscmin: The minimum short-circuit current expected on the line.

Ia: The current point is when the I/t graphic for the cable and fuse device cut. The mentioned graphic is not available, the $\mathbf{I_{f5}}$ current at which, after 5 seconds pass, the fuse opens, will be taken.

The short-circuit currents along the circuit depend on the short-circuit coming from the solar panels. A security factor will be defined to oversize the short-circuit and to make sure that it protects the cable even the currents are lower in practice.

$\mathbf{Factor_{security}}$: 1.25

For circuit breakers the following equations must be accomplished:

$$Breaking\ capacity > Iscmax \quad \textbf{(26)}$$

$$Iscmin > Ia \quad \textbf{(27)}$$

$$Iscmax < Ib \quad \textbf{(28)}$$

Where:

Ia: The current of activation of the magnetic device.

Ib: The current that corresponds to the value $\mathbf{(I^2t)_{adm}}$ of the conductor line measured on the circuit breaker graphic for (I^2t). The tolerable value for the conductor is:

$$(I^2 * t)_{Maxcable} = k^2 * S^2 \quad \textbf{(29)}$$

Let's choose the fuses for the system:

- **PV string to combiner fuse:**

We know that the strings of the panels are formed of 4 panels connected in series. The connection lines of all panels to the combiner are **6 mm** cross section.

Nominal current (A)	Current rating of fuse	Maximum tolerated current (A)*
9.46	12	46

Table 38: Fuse string to combiner

*For the suggested installation method **B1**

Where:

$$9.42 < 12 < 46 \text{ Valid}$$

$$I_2 = 1.6 * 12 = 19.2\ A$$

And:

$$1.45 * Iz = 66.7 \geq I_2 = 19.2 \quad \text{Valid}$$

The short-circuit currents of the chosen panel looking at **Tamesol** datasheet for the model is **TM-M672340**:

Isc: 9.46 A

The fuse should not cut the line when the string is on short-circuit mode, so as we see in Table 38 the **Isc** was considered the design current for the line.

The fuse should cut the line in the situation when the strings of panels connected in parallel starts to feed the string (in case of fault at that string), instead of supplying the consumption.

	N.Voltage (V)	Rpanel	Isc (A)	LineLength (m)	Section (mm)	pCopper	R.Panel-Combiner
String	151,04	15,9661734	9,46	15,53	6	0,02	0,04622024

Table 39: String and line short-circuit characteristics

Where:

N.voltage: The total voltage of 4 panels connected in series. In volts.

Rpanel: Which is the internal resistance of the panel at short-circuit instant.

$$\text{Rpanel} = \frac{\text{N. voltage}}{\text{Isc}} = \frac{151.04}{9.46} = 15.966\ \Omega$$

LineLength: The longest line installed for the different strings. Where in this case is **15.53 m**, which is the farthest string.

pCopper: The conductance of copper at 20ºC temperature. In **Ω***mm^2/m.

R.Panel-combiner: The resistance of the line connecting to the farthest string to the combiner. The following equation is used:

$$Resistance = \rho_{copper} * \frac{L}{Section} \quad \textbf{(30)}$$

Then the short-circuit for each group will differ considering the worst case scenario, for **Group 1** the fuse should protect the line of one string in case of 5 other strings short-circuited to it.

For **Group 2** the worst case scenario is 6 strings short-circuit to a single string. The total short-circuit current form each group will be:

$$Isc_{group} = (N - 1) * Isc * Factor_{security} \quad \textbf{(31)}$$

Then:

R5panels	3,19323467 Ω	R6panels	2,66102889 Ω
Group 1		Group 2	
Iscmax	Iscmin	Iscmax	Iscmin
59,125	58,2814101	70,95	69,7386871

Table 40: Short current for the farthest string on each group.

The chosen fuse has a breaking capability of **30 kA** and a **If5** of **30 A**.

For group 1:

$$30000\ A \gg Iscmax = 59.125\ A \quad Valid$$

$$Iscmin = 58.2814 > If5 = 30\ A \quad Valid$$

For group 2:

$$30000\ A \gg Iscmax = 70.95\ A \text{ Valid}$$

$$Iscmin = 69.738 > If5 = 30\ A \text{ Valid}$$

- **Lines combiner box to regulator fuses:**

The short-circuit possibilities in this part of the installation is that of short-circuit current to each array through the line connecting the combiner for each group and each group array regulator.

	N.Voltage	Rarray	Isc	LineLenght	Section	pCopper	R.Comb-Reg
Group 1-Regulator	151,04	2,66102889	56,76	12	35	0,02	0,006122449
	N.Voltage	Rarray	Isc	LineLenght	Section	pCopper	R.Comb-Reg
Group 2-Regulator	151,04	2,28088191	66,22	12	35	0,02	0,006122449

Table 41: Line from combiner to junction box characteristics.

Where the maximum expected short-circuit currents for both groups are the following:

Group 1		Group 2	
Iccmax	Iccmin	Iccmax	Iccmin
69,7386871	69,5813288	81,1309466	80,9180566

Table 42: Maximum and minimum Isc for both group arrays.

The chosen Fuse rating will be between the nominal current for each group **Isc** and the maximum tolerated current for the cable section of **35 mm**.

	Nominal current (A)	Fuse current rating (A)	Max tolerated current (A)*
Group 1	56.76	63	174
Group 2	66.22	80	174

Table 43: Fuse rating line from combiner to regulator.

*Installation method type **F**

The activation fuse will activate at:

$$I_2 = 1.6 * 80 = 128\ A \text{ and } I_2 = 1.6 * 63 = 100.8$$

$$1.45 * 174 = 252.3\ A$$

We see that for **group 1**:

$$I_2 = 127A \leq 1.45 * Iz = 252.3 \text{ Valid}$$

And for **group 2** :

$$I_2 = 128 < 1.45 * Iz = 252.3 \text{ Valid}$$

The fuse can handle the maximum possible short-circuit, knowing that the chosen model are: two fuses of **63** and **80 A** rating and fuse size **NH1**.

Looking at

Group 1		Group 2	
Iccmax	Iccmin	Iccmax	Iccmin
69,7386871	69,5813288	81,1309466	80,9180566

Table 42 we get the **Isc**:

Group 1 $Iscmax = 81.13\ A < Breaking\ capacity = 50000A$ Valid

$$If_5 = 225\ A > Iscmin = 81.11\ A\ \ Not\ valid$$

Group 2 $Iscmax = 69.738\ A < Breaking\ capacity = 50000\text{A}$ Valid

$$If5 = 300\ A > Iscmin = 69.72\ A\ \ Not\ valid$$

We can see that the fuses are capable of dealing with the maximum short-circuit currents due to the high breaking capability of the fuses, but they do not meet the second condition.

Although on other type of installation an addition protection measure should be installed to cover this weakness, in this case we see that the own conductor are capable of dealing with the **Iscmin** without passing the tolerance limit for the installation type suggested. So no extra protection is needed.

- **Line regulator to battery :**

Now for the lines connecting the two charge regulators to the battery system. The voltage changes to **48V** and so does the current. The maximum short-circuit what the line can suffer is when the battery system's reverse current circulates along the line in a short circuit between the line and the battery system.

	N.Voltage	Lenght	Section	Rreg-bat	Rtotalreg-bat
Regulator-Battery	48	2	35	0,00102041	0,000510204

Table 44: Line from the regulators to battery characteristics.

Where:

Rtotalreg-bat: Is the sum of both **Rreg-bat**, that is the resistance of the line of each of the two charge regulators to battery lines:

$$RTotal_{RegBat} = \frac{1}{\left(\frac{1}{R_{RegBat}}+\frac{1}{R_{RegBat}}\right)} \quad \textbf{(32)}$$

The **maximum short-circuit current** is the one that occurs at the union point of both lines from the charge regulators to the battery system.

The **minimum short-circuit current** is the one at the base of the charge regulator for each line, from the reverse current of the battery system.

	Regulator-Battery system			
	Psc (W)	In (A)	Iscmax (A)	Iscmin (A)
Group 1	90720	102,083333	2362,5	1878,498
Group 2	90720	102,083333	2362,5	1878,498

Table 45: Maximum and minimum short circuit currents.

Where:

In: is the maximum current that the regulator is able to transmit on a normal performance, being 4900 W the maximum PV power. Then: $In = \frac{4900\,W}{48\,V} = 102.0833\,A$

Psc: The Short-Circuit power output of the battery system:

$$Psc = VoltageBattery * Isc_{C1hour} * 10\ batteries\ in\ parallel = 48 * 189 * 10 = 90720\,W$$

Isc: **Iscma**x with security factor and the **minimum Isc** without it.

$$Iscmax = Factor_{security} * \frac{Psc}{48\,V} = 1.25 * 1890 = 2362{,}5\,A$$

The chosen fuse for the two lines is the following:

Nominal current (A)	Fuse current rating(A)	Max tolerated current (A)*
102.08	125	174

Table 46: Fuse caliber for the line from regulator to battery.

*Method **F** of installation

Where:

$$I_2 = 1.6 * In = 1.6 * 125 = 200\,A$$

$$1.45 * Iz = 252.3 > I_2\ Valid$$

The short-circuit protection from the fuse:

$$Breaking\ capacity = 50000\,A \gg Iscmax\ \ Valid$$

$$If5 = 500A < Iscmin\ for\ both\ lines\ \ Valid$$

- **Line from battery system to inverter:**

The union line between the battery system and the inverter presents the following characteristics:

	N.Voltage	Length (m)	Section (mm)	Rbat-inv
Battery-Inverter	48	2	70	0,00102041

Table 47: Connection line between batteries and Inverter characteristics.

Where the maximum and minimum **Isc** are the following:

Battery system-Inverter			
Psc	Inominal	Iscmax	Iscmin
90720	203,255208	2362,5	1888,073394

Table 48: Expected short-circuit currents at the line.

The **Iscmin** is the one at inverter level and the **Iscmax** will be the one at battery level, where Iscmax has been calculated:

$$Iscmin = \frac{Psc}{(48\,V * (1 + R_{BatInv}))}$$

The chosen fuse will be the following:

Nominal current (A)	Caliber of the fuse (A)	Maximum tolerated current (A)*
203,255	250	269

Table 49: Fuse rating for the line battery-inverter.

*Type **F** installation

Where:

$$I_2 = 1.6 * 250 = 400\ A$$

$$1.45 * Iz = 269\ A < I_2\ \ No\ Valid$$

The protection against short-circuit:

$$Isc_{max} \ll Breaking\ capacity = 33000\ A\ \ Valid$$

$$If_5 = 800\ A\ < Iscmin\ \ Valid$$

- **Line from Inverter to distribution panel fuse:**

Where :

Cable inverter-distribution panel					
Power (W)	Voltage	Inominal	Section (mm)	Length (m)	RInvDist
9756,25	230	42,4184783	6	1	0,00297619

Table 50: Characteristics of the line from the Inverter to the distribution panel.

The **Isc** are:

Psc(W)	Voltage(V)	Iscmax(A)	Iscmin(A)
90720	230	493,0434	393,264

Table 51: Isc at the Inverter to distribution panel.

Let’s choose the needed fuse:

Nominal current (A)	Fuse current rating (A)	Max tolerated current (A)*
42.4184	50	57

Table 52: Fuse rating

*For **E** type installation

Where:

$$I_2 = 1.6 * 50 = 80\ A$$

$$1.45 * Iz = 82.65 > I_2\ \ Valid$$

Now the short circuit protection from the fuse:

$$Iscmax = 100.095 \ll Breaking\ capacity = 50000\ A\ Valid$$

$$If_5 = 150\ A < Iscmin\ \ Valid$$

Further protection from a circuit breaker is needed:

- **Lines from distribution panel to consumption:**

The characteristic of the lines going to the electrical consumptions are:

	Power	Length	Current	Section	ResistanceLine
Home	7006,25	14	30,4619565	6	0,04166667
	Power	Lenght	Current	Section	ResistanceLine
Production	2750	50	11,9565217	6	0,14880952

Table 53: Lines from the distribution panels to the consumptions, characteristics.

The short-circuit will be the one at the distribution panel, which is the **Iscmax**, and the minimum **Isc** at the end of the line due to the resistance of the line itself.

	Iscmax	Iscmin
House	491,580	377,578
Production	491,580	342,455

Table 54: Isc in the consumption lines.

Where the **Iscmax** is the one at the distribution panel level, and **Iscmin is** the one at the end of each line:

$$Iscmin_{linesAC} = \frac{Psc}{\left(48\,V * (1 + RInverterDist + RLine)\right)}$$

Then the chosen fuse will be the following:

Nominal current (A)	Fuse rating (A)	Max tolerated current (A)*
30.46	32	46
11.95	15	46

*****Installation type **B1**

For the house the fuse rating of **32 A** fuse size is 14x51 and **15 A** fuse size is 10x38 for the production part.

$$I_{2house} = 1.6 * 32 = 51.2\,A \;\; and\; I_{2production} = 1.6 * 15 = 24\,A$$

Then:

$$Iz * 1.45 = 66.7\,A \;\; \boldsymbol{Valid\ for\ both\ of\ them}$$

The fuses have a breaking capacity of **30 kA** for the **15 A** rated fuse and **10kA** for the **32 A** one. So as we can see they are much higher than the **Iscmax** so they are valid.

On the other protection condition:

For the production part $If_5 = 45\,A < Iscmin_{withoutsecurityfactor} = 219.24\,A \quad Valid$

For the house part $If_5 = 80\,A \; < Iscmin_{Withoutsecurityfactor} = 241.73\,A \quad Valid$

- **Line to the wind turbine protection**

The maximum tolerated currents for the battery system to turbine charge regulator and for the line from the charge regulator to the turbine are the reverse current of the short-circuit with the battery system:

Nominal current (A)	Fuse rating (A)	Max tolerated current (A)*
62.5	80	327*
62.5	80	140*

Figure 37: Lines from battery system to wind turbine currents.

*Type **F** installation

$$I_2 = 1.6 * 80 = 128\ A$$

$$Iz * 1.45 = 140 * 1.45 = 203\ A > I_2\ \boldsymbol{Valid\ for\ both\ lines}$$

Now the protection against short currents:

Wind turbine to Charge regulator					
Power (W)	Voltage	Current (A)	Section(mm)	Length (m)	ResistanceLine
3000	48	62,5	95	20	0,003759398
Charge regulator to battery system					
Power (W)	Voltage	Current (A)	Section(mm)	Length (m)	Resistanceline
3000	48	62,5	25	2	0,001428571

Table 55: Lines from battery system to wind turbine characteristics.

And:

Wind turbine to regulator			
Psc	Voltage	Iscmax	Iscmin
90720	48	2359,12981	1880,24534
Battery system to regulator			
Psc	Voltage	Iscmax	Iscmin
90720	48	2362,5	1887,30385

Table 56: Expected Isc currents at the lines of the wind turbine.

$$Breakin\ capacity = 50000\ A \gg Iscmax\ \ Valid\ for\ both\ lines$$

$$If_5 = 300\ A < 1023.75\ A\ and\ < 1208.27\ A \quad Valid\ for\ both\ lines$$

2.10. Grounding

The grounding should guarantee that the contact voltage when a defect occurs is of **24 V**, this in addition to the differential protection at the house and production area considering a sensibility of **30 mA** from the protections (following the Spanish legislation) .

$$R_{GroundingDC} = \frac{24\ V}{0.03\ A} = 800\ \Omega$$

The grounding for the DC can be made through a TN-S connection to ease the installation. It will connect to the grounding the neutral and masses of the solar panel, the masses of the combiner boxes, wind turbine mass and its charge controller and the charge regulators for the PV system.

Let's see the sizing of a vertically disposed plate for the installation of the grounding:

$$R_{Grounding} = \frac{0.8*\rho}{L} \quad \textbf{(33)}$$

P: The resistivity of the terrain. For this case a farming terrain not to humid, the parameter will be **10 Ωm**

L: The perimeter of the plate.

$$L = \frac{150 * 0.8}{800} = 0.15\ m$$

The plate is 2 mm wide.

Others:

2.11. Selection of solar panel model

The selection of panels will be between a series of panels considered to be installed. The models considered are the following by the manufacturer companies:

Tamesol:

Three models from the family **TM-M672** 320, 325 and 340 W

AE Solar GmbH:

Two models: **AE305P6-72** of 305 W and **AE310P6-72** power output 310 W

The prices for the solar panels are taken from **Enfsolar**'s database [33]

Power to install (W)	Panel model	Price of panel (€/Wp)	Power panel	Monthly irrad (Wh/m²)	Panels needed	Price (€)
33401,3822	TM-M672320	0,378	320	1910	55	6.652,80 €
33401,3822	TM-M672325	0,378	325	1910	54	6.633,90 €
33401,3822	TM-M672340	0,378	340	1910	52	6.683,04 €
33401,3822	AE305P6-72	0,39	305	1910	58	6.899,10 €
33401,3822	AE310P6-72	0,39	310	1910	57	6.891,30 €

Table 57: The comparison of solar panels. Source: Own

In Table 57 we can see the difference in price among the different models. We can reject the models from the **AE Solar Gmbh** company, since they are more expensive than the ones from the **Tamesol** family of monocrystalline.

Selecting between the three types of panels from the same family is not just about money, we have to take into account that the amount of the panels are pretty high, the difference in price among the three of them are pretty low, that the model that needs the least amount of panels to supply the needed power is also preferable (due that the installation will be on the roof).

But the definitive factor for selecting the panel model is the amount of charge controllers depending on how we organize them.

The considered charge regulators as we stablished before are the models **SmartSolar 250/100**, **250/85**, **150/100** and **150/85**. For more information about the calculation process see Charge regulator.

	Panel parameters		Regulator characteristics							
	Vosc	Icc	Voltage		Current		Series		Parallel	
TM-M672320	46,62	8,94	250	150	85	100	4	2	7	8
TM-M672325	46,67	9,07	250	150	85	100	4	2	7	8
TM-M672340	46,8	9,46	250	150	85	100	4	2	7	8

Table 58: Number of panels in parallel and series by charge regulator. Source: Own.

In Table 58 we see that the regulator allows the same amount of panels in parallel and series connection for the three types of panels, dividing the maximum amount of panels each regulator can take, thus we obtain the number of regulators needed:

Amount of Regulators					
Number panels	250/100	250/85	150/100	150/85	
55	1,71875	1,96428571	3,4375	3,92857143	TM-M672320
54	1,6875	1,92857143	3,375	3,85714286	TM-M672325
52	1,625	1,85714286	3,25	3,71428571	TM-M672340

Table 59: Amount of regulators needed by solar panel model. Source: Own

Watching Table 59 we would select the model **TM-M672325** as it is the cheapest one, and needed two **SmartSolar 250/85** as the other two but the problems comes when organizing the panels **TM-M672320** and **TM-M672325** due that the number of panels needed for each model is 55 and 54 respectively.

The problem is that we cannot organize the numbers 55 and 54 in combinations that give an integer number using only two regulators with the proposed models: e.g for the 55 panels group.

Possible combinations would be 32+23, 31+24, 30+25 and 29+28 doing the basic math of diving the previous numbers between the maximum allowed of panels possible in series by each charge regulator we can see we never get an integer number.

So if we choose those two models we would need three charge regulators even it sounds unintuitive.

But the model **TM-M672340**, which needs 52 can be organized in two groups of 28+24 that can use only two regulators, which is the cheapest solution. Therefore the chosen model for the installation is the model **TM-M672340** of 340 W.

2.12. Selection between Li-ion and Lead acid technologies for the battery system

The selection of the energy storage technology will mainly be about which configuration grants an optimal solution with the least possible investment on the long run.

For the solar installation the **12 CS 11P** lead-acid battery by the **Rolls** company and the **RESU 10** Li-ion battery by **LG Chem**. Battery's life cycles vary depending on different factors, this will determine the life expectancy of the battery system and therefore the amount of times it will be needed to be changed.

Model	DOD (%)	Life expectancy (cycles)
RESU 10	90 %	6250
12 CS 11 P	60 %	3000

Table 60: Batteries life expectancy. Source: Manufacturers

Considering around 350 cycles/year for the battery system, we can obtain the number of years they will last:

$$Life_{12CS11P} = \frac{3000}{350} = 8.57\ years \cong 9\ years$$

$$Life_{RESU10} = \frac{6250}{350} = 17.85\ years \cong 18\ years$$

The whole solar system's investment is expected to last for at least 18-20 years. So the Li-ion battery is just within this time period, on the other hand the lead-acid battery system will have to be changed half way through.

Model	Changes	Number of batteries*	Price with Tax (€)**
RESU 10	0	10	5000*10=50000 €
12 CS 11 P	1	24+24=48	1144*48=54912 €

Table 61: Battery prices

*The number of batteries is the sum of all battery used along the 18-20 years period.

**The price for the lead-acid's battery change doesn't take into account monetary inflation.

So the **RESU 10** battery will be the cheapest solution, taking into account that the savings are not only directly price related, but also there will be savings in relation to the installation of the second battery group for the lead-acid ones etc…

2.13. Distance between panels on roof installation

Although normally on roof installation the solar panels are installed at the same angle as the roof, and there is no separation between panels is needed, in this case the panels are suggested to be installed at a 50º degree angle, which is 5° more than the roof angle of around 40-45º. Then a separation is needed between the panels to avoid shadowing.

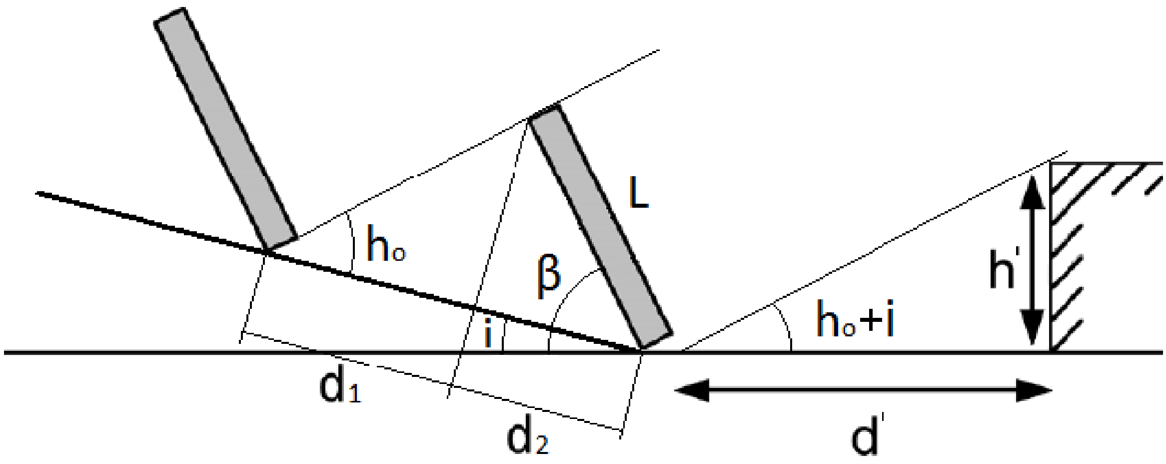


Figure 38: Distance to avoid shadowing in inclined installation. Source: IDAE[32]

The following calculation process:

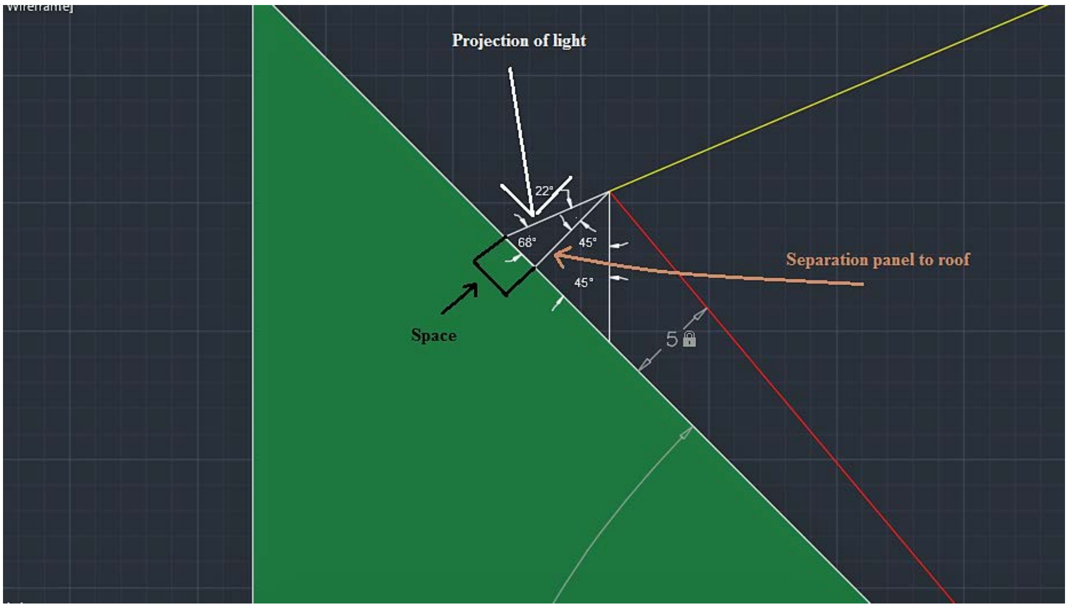


Figure 39: Light projection in winter on the panels. Source: Own creation

The explanation of Figure 38:

Yellow line: Represents the sunlight in winter (the worst scenario) where the light presents a 23º angle with the ground (horizontal axis).

Red line: Represents the solar panel. The chosen model is 1,956 m long. The panel is at a 5º degree with the roof surface and at a 50º angle with the horizontal axis.

Projection of Light (PL): The distance that the light travels since it "touches" the solar panel and ends at the roof surface.

Space (d): The minimum distance to separate the upper panel to avoid shadowing.

Separation panel to roof (SPR): The vertical distance of the highest part of the solar panel in respect to the local axis located on the roof surface.

The calculation of the minimum space needed will be as follows:

$SPR = Panel_{Lenght} * \sin PanelToSurface \ (mm)$ **(34)**

Being:

PanelToSurface: The angle between the panel and the surface is **5º**.

PanelLength: 1956 mm

$$SPR = 1956 * \sin 5° = 170.47\, mm$$

We calculate now the previously stated Projection of the light:

$$PL = \frac{SPR}{\sin 68°} \ (mm) \quad \textbf{(35)}$$

$$PL = \frac{170.47}{\sin 68°} = 183.857\, mm$$

Now to finish the minimum space needed to be left between the solar panels :

$$Space = PL * \cos 68° \quad \textbf{(36)}$$

$$Space = 183.857 * \cos 68° = 68.874\, mm \approx 70\, mm$$

The angle of the roof is between 45 to 40 degrees. Therefore the minimum space needed should be bigger for safety reasons.

Then the total space measured from the base of the first line of panels is:

$$Space_{total} = Space + Panel_{lengthsurface} \quad \textbf{(37)}$$

Being $Panel_{lengthsurface}$: The projection of the first line of panels' length upon the roof surface:

$$Panel_{lengthsurface} = Panel_{length} * \cos\left(Angle_{panel} - Angle_{Roof}\right) \quad \textbf{(38)}$$

$$Panel_{lengthsurface} = 1956\ mm * \cos(50° - 45°) = 1948.55\ mm$$

$$Space_{total} = 70\ mm + 1948.55\ mm = 2018.55\ mm$$

Then:

$$Space_{totalSecurity} = Space_{total} * Factor_{Security} \quad \textbf{(39)}$$

Factor$_{\textbf{Security}}$= 1.25

$$Space_{totalSecurity} = 2018.55\ mm * 1.25 = 2523.19\ mm \approx 2523\ mm = 2.523\ m$$

2.14. Annexes:

TECSUN (PV) PV1-F

Selection and ordering data

Nominal cross-section and colour	Order No.	Conductor diameter	Overall diameter of cable Min.value	Overall diameter of cable Max.value	Approx. net weight	Minimum bending radius	Maximum permissible tensile load	Current carrying capacity at 60° C ambient temperature (free air)	Permissible short circuit current (1s)
		[mm]	[mm]	[mm]	[kg/km]	[mm]	[N]	[A]	[kA]
1.5 mm² black	5DH93011	1.6	4.4	4.8	29	14.4	23	29	0.19
1.5 mm² blue	5DH93012	1.6	4.4	4.8	29	14.4	23	29	0.19
1.5 mm² red	5DH93013	1.6	4.4	4.8	29	14.4	23	29	0.19
2.5 mm² black	5DH93012	1.9	4.7	5.1	43	15.3	38	41	0.32
2.5 mm² blue	5DH93022	1.9	4.7	5.1	43	15.3	38	41	0.32
2.5 mm² red	5DH93023	1.9	4.7	5.1	43	15.3	38	41	0.32
4.0 mm² black	5DH93031	2.4	5.2	5.6	58	16.8	60	55	0.50
4.0 mm² blue	5DH93032	2.4	5.2	5.6	58	16.8	60	55	0.50
4.0 mm² red	5DH93033	2.4	5.2	5.6	58	16.8	60	55	0.50
6.0 mm² black	5DH93041	2.9	5.7	6.1	76	18.3	90	70	0.76
6.0 mm² blue	5DH93042	2.9	5.7	6.1	76	18.3	90	70	0.76
6.0 mm² red	5DH93043	2.9	5.7	6.1	76	18.3	90	70	0.76
10 mm² black	5DH93051	4.0	6.8	7.2	120	21.6	150	98	1.26
16 mm² black	5DH93061	5.5	8.3	9.0	178	36	240	132	2.01
25 mm² black	5DH93071	6.4	10.0	10.7	273	43	375	176	3.15
35 mm² black	5DH93081	7.5	11.1	11.8	364	47	525	218	4.41
50 mm² black	5DH93091	9.0	12.6	13.3	500	53	750	276	6.30
70 mm² black	5DH93101	10.8	14.4	15.2	686	61	1050	347	8.82
95 mm² black	5DH93111	12.6	16.2	17.0	899	68	1425	416	12.0
120 mm² black	5DH93121	14.3	17.7	18.7	1131	75	1800	488	15.1
150 mm² black	5DH93131	15.9	19.7	20.7	1382	83	2250	566	18.9
185 mm² black	5DH93141	17.5	21.3	22.3	1669	89	2775	644	23.3
240 mm² black	5DH93151	20.5	24.2	25.5	2208	102	3600	775	30.4

Controlador de carga SmartSolar	MPPT 250/60	MPPT 250/70	MPPT 250/85	MPPT 250/100
Tensión de la batería	Ajuste automático a12, 24 ó 48V (Se precisa una herramienta de *software* para ajustar el sistema en 36V)			
Corriente de carga nominal	60A	70A	85A	100A
Potencia FV máxima, 12 V 1a,b)	860W	1000W	1200W	1450W
Potencia FV máxima, 24 V 1a,b)	1720W	2000W	2400W	2900W
Potencia FV máxima, 48 V 1a,b)	3440W	4000W	4900W	5800W
Máxima corriente de corto circuito	35A (máx. 30A x con. MC4)		70A (max 30A x MC4 con.)	
Tensión máxima del circuito abierto FV	250V máximo absoluto en las condiciones más frías 245V en arranque y funcionando al máximo			
Eficacia máxima	99%			
Autoconsumo	Menos de 35mA a 12V / 20mA a 48V			
Tensión de carga de "absorción"	Valores predeterminados: 14,4 / 28,8 / 43,2 / 57,6V (Regulable con: selector giratorio, pantalla, VE.Direct o Bluetooth)			
Tensión de carga de "flotación"	Valores predeterminados: 13,8 / 27,6 / 41,4 / 55,2V (Regulable con: selector giratorio, pantalla, VE.Direct o Bluetooth)			
Algoritmo de carga	adaptativo multifase			
Compensación de temperatura	-16 mV / -32 mV / -68 mV / °C			
Protección	Polaridad inversa de la batería (fusible, no accesible por el usuario) Polaridad inversa/Cortocircuito de salida/Sobretemperatura			
Temperatura de trabajo	-30 a +60°C (potencia nominal completa hasta los 40°C)			
Humedad	95%, sin condensación			
Puerto de comunicación de datos	VE.Direct o Bluetooth			
Interruptor on/off remoto	Sí (conector bifásico)			
Relé programable	DPST Capacidad nominal CA 240 V AC / 4 A Capacidad nominal CC 4 A hasta 35 V CC, 1 A hasta 60 V CC			
Funcionamiento en paralelo	Sí (no sincronizado)			
CARCASA				
Color	Azul (RAL 5012)			
Terminales FV 3)	35mm² / AWG2 (modelos Tr), Dos pares de conectores MC4 (modelos MC4 de 250/60 y 250/70) Tres pares de conectores MC4 (modelos MC4 de 250/85 y 250/100)			
Bornes de batería	35mm² / AWG2			
Grado de protección	IP43 (componentes electrónicos), IP22 (área de conexión)			
Peso	3 kg		4,5 kg	
Dimensiones (al x an x p) en mm	Modelos Tr: 185 x 250 x 95 mm Modelos MC4: 215x250x95 mm		Modelos Tr: 216 x 295 x 103 mm Modelos MC4: 246x295x103 mm	
NORMATIVAS				
Seguridad	EN/IEC 62109			

1a) Si se conecta más potencia FV, el controlador limitará la potencia de entrada al máximo estipulado.
1b) La tensión FV debe exceder en 5 V la Vbat (tensión de la batería) para que arranque el controlador.
Una vez arrancado, la tensión FV mínima será de Vbat + 1 V.
2) Un conjunto FV con una corriente de corto circuito superior puede dañar el controlador.
3) Modelos MC4: se podrían necesitar varios separadores para conectar en paralelo las cadenas de paneles solares.
Corriente máximo por conector MC4: 30A (los conectores MC4 están conectados en paralelo a un rastreador MPPT)

Inversor Phoenix	C12/1200 C24/1200	C12/1600 C24/1600	C12/2000 C24/2000	12/3000 24/3000 48/3000	24/5000 48/5000
Funcionamiento en paralelo y en trifásico	Sí				
INVERSOR					
Rango de tensión de entrada (V DC)	9,5 – 17V 19 – 33V 38 – 66V				
Salida	Salida: 230V ± 2% / 50/60Hz ± 0,1% (1)				
Potencia cont. de salida 25ºC (VA) (2)	1200	1600	2000	3000	5000
Potencia cont. de salida 25ºC (W)	1000	1300	1600	2400	4000
Potencia cont. de salida 40ºC (W)	900	1200	1450	2200	3700
Potencia cont. de salida 65ºC (W)	600	800	1000	1700	3000
Pico de potencia (W)	2400	3000	4000	6000	10000
Eficacia máx. 12/ 24 /48 V (%)	92 / 94 / 94	92 / 94 / 94	92 / 92	93 / 94 / 95	94 / 95
Consumo en vacío 12 / 24 / 48 V (W)	8 / 10 / 12	8 / 10 / 12	9 / 11	20 / 20 / 25	30 / 35
Consumo en vacío en modo AES (W)	5 / 8 / 10	5 / 8 / 10	7 / 9	15 / 15 / 20	25 / 30
Consumo en vacío modo Search (W)	2 / 3 / 4	2 / 3 / 4	3 / 4	8 / 10 / 12	10 / 15
GENERAL					
Relé programable (3)	Sí				
Protección (4)	a – g				
Puerto de comunicación VE.Bus	Para funcionamiento paralelo y trifásico, supervisión remota e integración del sistema				
On/Off remoto	Sí				
Características comunes	Temperatura de funcionamiento: -40 a +65ºC (refrigerado por ventilador) Humedad (sin condensación): Máx. 95%				
CARCASA					
Características comunes	Material y color: aluminio (azul RAL 5012) Tipo de protección: IP 21				
Conexiones de la batería	cables de batería de 1,5 metros se incluye		Pernos M8	2+2 Pernos M8	
Conexiones 230 V CA	Enchufe G-ST18i		Abrazadera-resorte	Bornes atornillados	
Peso (kg)	10		12	18	30
Dimensiones (al x an x p en mm.)	375x214x110		520x255x125	362x258x218	444x328x240
NORMATIVAS					
Seguridad	EN 60335-1				
Emisiones / Inmunidad	EN 55014-1 / EN 55014-2				
Directiva de automoción	2004/104/EC	2004/104/EC		2004/104/EC	

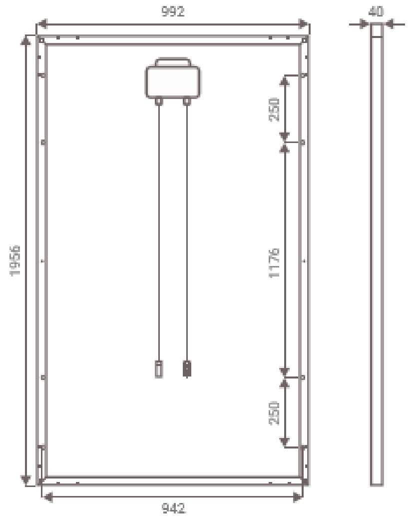
1) Puede ajustarse a 60 Hz, y a 240 V.
2) Carga no lineal, factor de cresta 3:1
3) Relé programable que puede configurarse en alarma general, subtensión de CD o como señal de arranque de un generador (es necesario el interfaz MK2 y el software VEConfigure)
Capacidad nominal CA 230V / 4A
Capacidad nominal CC 4 A hasta 35VDC, 1 A hasta 60VDC

4) Protección:
a) Cortocircuito de salida
b) Sobrecarga
c) Tensión de la batería demasiado alta
d) Tensión de la batería demasiado baja
e) Temperatura demasiado alta
f) 230 V CA en la salida del inversor
g) Ondulación de la tensión de entrada demasiado alta

TM-M672320/340

MONOCRYSTALLINE PV MODULES

TM-Series



GENERAL CHARACTERISTICS

Dimensions	1956x992x40 mm
Weight	23 Kg

PACKAGING

Modules per Pallet	22
Nº pallets per HC Container 40'	24

The max capacity per container are 628 modules

TEMPERATURE RATING

NOCT	45 ± 2º C
Coefficent of (Pmax)	-0.48 %/ºC
Coefficent of (Voc)	-0.34 %/ºC
Coefficent of (Isc)	+0.037 %/ºC

CERTIFICATIONS

IEC 6125, IEC 61730, ISO 9001:2008, ISO 14001:2004, BS OHSAS 18001:27, PV Cycle, UL, MCS, PID, WEEE.

ELECTRICAL DATA

STC	TM M672320	TM M672325	TM M672330	TM M672335	TM M672340
Maximum Power at STC (Pmax)	320 W	325 W	330 W	335 W	340 W
Optimum Operating Voltage (Vmp)	36.60 V	37.64 V	37.68 V	37.72 V	37.76 V
Optimum Operating Current (Imp)	8.51 A	8.63 A	8.75 A	8.88 A	9.00 A
Open Circuit Voltage (Voc)	46.62 V	46.67 V	46.72 V	46.75 V	46.80 V
Short Circuit Current (Isc)	8.94 A	9.07 A	9.20 A	9.33 A	9.46 A
Module Efficency	16.49 %	16.74 %	17 %	17.25 %	17.51 %

Electric characteristics at normal standard conditions (STC)
STC Conditions: Irradiance: 1.000W/m2, cell temperature: 25ºC, AM=1.5

NOCT	TM M672320	TM M672325	TM M672330	TM M672335	TM M672340
Maximum Power at NOCT (Pmax)	236 W	240 W	243 W	247 W	251 W
Optimum Operating Voltage (Vmp)	34.59 V	35.57 V	35.61 V	35.65 V	35.68 V
Optimum Operating Current (Imp)	6.64 A	6.73 A	6.83 A	6.93 A	7.02 A
Open Circuit Voltage (Voc)	43.78 V	43.82 V	43.87 V	43.90 V	43.90 V
Short Circuit Current (Isc)	7.20 A	7.30 A	7.41 A	7.51 A	7.62 A

Electric characteristics at normal operation conditions (NOCT)
NOCT Conditions: Irradiance: 800W/m2, ambient temperature: 20ºC, AM=1.5, wind speed: 1m/s

OPERATIVE CONDITIONS

Power Tolerance	0/+5W
Max. System Voltage	1.000 V
Max. Series Fuse Rating	15 A
Operating Temperature Range	-40º C to 85 ºC
Max. Static Load, Front (Snow)	5400 Pa
Max. Static Load, Back (Wind)	2400 Pa
Fire Rating	Class A

MECHANICAL CHARACTERISTICS

Solar Cells	Monocrystalline silicon 156x156 mm
Cell Arrangement	72 cells in series
Front Cover	Low-iron tempered glass 3.2 mm
Frame	Anodized aluminum alloy
Encapsulant	EVA (ethylene vinyl acetate)
Junction Box	IP65
Bypass Diodes	3
Cables (lenght/area)	1000 mm / 4 mm^2 (IEC), 12 AWG (UL)
Connectors	MC4

Fusibles fotovoltaicos
Curva gPV
de 1 a 600 A

Referencias
Fusibles gPV cilíndricos

Calibre (A)	Tensión asignada U DC (V)	Potencia disipada W@ In	W@ 0,8 In	Poder de corte	10 x 38 Referencia	14 x 51 Referencia
1	1000	0,76	0,43	30 kA	60PV 0001	
2	1000	1,54	0,84	30 kA	60PV 0002	
3	1000	1,35	0,74	30 kA	60PV 0003	
4	1000	1,84	1,08	30 kA	60PV 0004	
6	1000	2,50	1,40	30 kA	60PV 0006	
8	1000	2,57	1,47	30 kA	60PV 0008	
10	1000	2,58	1,51	30 kA	60PV 0010	
12	1000	2,61	1,42	30 kA	60PV 0012	
15	1000	2,44	1,08	30 kA	60PV 0015	
16	1000	2,70	1,56	30 kA	60PV 0016	
20	1000	2,99	1,75	30 kA	60PV 0020	
25	1000	5,1	2,7	10 kA		60PV 0C25
32	1000	6,2	3,3	10 kA		60PV 0C25

Fusible gPV de cuchillas

Calibre (A)	Tensión asignada U DC (V)	Potencia disipada W@ In	W@ 0,8 In	Poder de corte	Talla NH1 Referencia	Talla 2XL Referencia	Talla 3L Referencia
32	1000	8,5	4,3	50 kA	60PV 0032		
40	1000	9	4,6	50 kA	60PV 0040		
50	1000	10,5	5,4	50 kA	60PV 0050		
63	1000	12	6,1	50 kA	60PV 0063		
80	1000	15,5	7,9	50 kA	60PV 0080		
100	1000	16,5	8,4	50 kA	60PV 0100		
125	1000	17,5	8,9	50 kA	60PV 0125		
160	1000	24	12,2	50 kA	60PV 0160		
200	1000	50	28	33 kA		60PV 0200	
250	1000	60	34	33 kA		60PV 0250	
315	1000	66	40	33 kA		60PV 0315	
355	1000	68	42	50 kA		60PV 0355	
400	1000	82	48	50 kA			60PV 0400
500	1000	85	50	50 kA			60PV 0500
600	1000	118	92	50 kA			60PV 0600

Descripción de accesorios	Talla NH1 Referencia	Talla 2XL Referencia	Talla 3L Referencia
Contacto auxiliar de señalización de fusión fusibles	56PV 9901	56PV 9901	56PV 9901
Soporte recomendado	65PV 1011	65PV 1112	65PV 1113

Scope statements

Instalaciones de

Energía Solar Fotovoltaica

Pliego de Condiciones Técnicas de Instalaciones Aisladas de Red

PCT-A-REV - febrero 2009

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Antecedentes

Esta documentación, realizada en colaboración entre el departamento de energía solar de IDAE y CENSOLAR, es una revisión del Pliego de Condiciones Técnicas de Instalaciones Aisladas de Red, editado en octubre de 2002, y que fue realizado por el Departamento de Energía Solar del IDAE, con la colaboración del Instituto de Energía Solar de la Universidad Politécnica de Madrid y del Laboratorio de Energía Solar Fotovoltaica del Departamento de Energías Renovables del CIEMAT.

Su finalidad es establecer las condiciones técnicas que deben tomarse en consideración en la Convocatoria de Ayudas para la promoción de instalaciones de Energía Solar Fotovoltaica, en el ámbito del Plan de Fomento de las Energías Renovables correspondiente al periodo 2005-2010.

Índice

1. Objeto

1.1 Fijar las condiciones técnicas mínimas que deben cumplir las instalaciones fotovoltaicas aisladas de la red, que por sus características estén comprendidas en el apartado segundo de este Pliego. Pretende servir de guía para instaladores y fabricantes de equipos, definiendo las especificaciones mínimas que debe cumplir una instalación para asegurar su calidad, en beneficio del usuario y del propio desarrollo de esta tecnología.

1.2 Se valorará la calidad final de la instalación por el servicio de energía eléctrica proporcionado (eficiencia energética, correcto dimensionado, etc.) y por su integración en el entorno.

1.3 El ámbito de aplicación de este Pliego de Condiciones Técnicas (en lo que sigue, PCT) se aplica a todos los sistemas mecánicos, eléctricos y electrónicos que forman parte de las instalaciones.

1.4 En determinados supuestos del proyecto se podrán adoptar, por la propia naturaleza del mismo o del desarrollo tecnológico, soluciones diferentes a las exigidas en este PCT, siempre que quede suficientemente justificada su necesidad y que no impliquen una disminución de las exigencias mínimas de calidad especificadas en el mismo.

1.5 Este PCT está asociado a las líneas de ayuda para la promoción de instalaciones de energía solar fotovoltaica en el ámbito del Plan de Energías Renovables.

2. Generalidades

1.6 Este Pliego es de aplicación, en su integridad, a todas las instalaciones solares fotovoltaicas aisladas de la red destinadas a:

– Electrificación de viviendas y edificios
– Alumbrado público
– Aplicaciones agropecuarias
– Bombeo y tratamiento de agua
– Aplicaciones mixtas con otras fuentes de energías renovables

1.7 También podrá ser de aplicación a otras instalaciones distintas a las del apartado 2.1, siempre que tengan características técnicas similares.

1.8 En todo caso es de aplicación toda la normativa que afecte a instalaciones solares fotovoltaicas:

1.8.1 Real Decreto 842/2002, de 2 de agosto, por el que se aprueba el Reglamento Electrotécnico para Baja Tensión (B.O.E. de 18-9-2002).

1.8.2 Código Técnico de la Edificación (CTE), cuando sea aplicable.

1.8.3 Directivas Europeas de seguridad y compatibilidad electromagnética.

3. Definiciones

3.1.1 *Radiación solar*

Energía procedente del Sol en forma de ondas electromagnéticas.

3.1.2 Irradiancia

Densidad de potencia incidente en una superficie o la energía incidente en una superficie por unidad de tiempo y unidad de superficie. Se mide en kW/m^2.

3.1.3 Irradiación

Energía incidente en una superficie por unidad de superficie y a lo largo de un cierto período de tiempo. Se mide en MJ/m^2 o kWh/m^2.

3.1.4 Año Meteorológico Típico de un lugar *(AMT)*

Conjunto de valores de la irradiación horaria correspondientes a un año hipotético que se construye eligiendo, para cada mes, un mes de un año real cuyo valor medio mensual de la irradiación global diaria horizontal coincida con el correspondiente a todos los años obtenidos de la base de datos.

3.2 Generadores fotovoltaicos

3.2.1 Célula solar o fotovoltaica

Dispositivo que transforma la energía solar en energía eléctrica.

3.2.2 Célula de tecnología equivalente *(CTE)*

Célula solar cuya tecnología de fabricación y encapsulado es idéntica a la de los módulos fotovoltaicos que forman el generador fotovoltaico.

3.2.3 Módulo fotovoltaico

Conjunto de células solares interconectadas entre sí y encapsuladas entre materiales que las protegen de los efectos de la intemperie.

3.2.4 Rama fotovoltaica

Subconjunto de módulos fotovoltaicos interconectados, en serie o en asociaciones serie-paralelo, con voltaje igual a la tensión nominal del generador.

3.2.5 *Generador fotovoltaico*

Asociación en paralelo de ramas fotovoltaicas.

3.2.6 Condiciones Estándar de Medida *(CEM)*

Condiciones de irradiancia y temperatura en la célula solar, utilizadas como referencia para caracterizar células, módulos y generadores fotovoltaicos y definidas del modo siguiente:

Irradiancia (G_{STC}): 1000 W/m^2

Distribución espectral: AM 1,5 G

Incidencia normal

– Temperatura de célula: 25 °C

3.2.7 ***Potencia máxima del generador (potencia pico)***

Potencia máxima que puede entregar el módulo en las CEM.

3.2.8 *TONC*

Temperatura de operación nominal de la célula, definida como la temperatura que alcanzan las células solares cuando se somete al módulo a una irradiancia de 800 W/m^2 con distribución espectral AM 1,5 G, la temperatura ambiente es de 20 °C y la velocidad del viento de 1 m /s.

3.3 Acumuladores de plomo-ácido

3.3.1 *Acumulador*

Asociación eléctrica de baterías.

3.3.2 *Batería*

Fuente de tensión continua formada por un conjunto de vasos electroquímicos interconectados.

3.3.3 *Autodescarga*

Pérdida de carga de la batería cuando ésta permanece en circuito abierto. Habitualmente se expresa como porcentaje de la capacidad nominal, medida durante un mes, y a una temperatura de 20 °C.

3.3.4 *Capacidad nominal*: C_{20} (Ah)

Cantidad de carga que es posible extraer de una batería en 20 horas, medida a una temperatura de 20 °C, hasta que la tensión entre sus terminales llegue a 1,8 V /vaso. Para otros regímenes de descarga se pueden usar las siguientes relaciones empíricas: C_{100}/C_{20} • 1,25, C_{40}/C_{20} • 1,14, C_{20}/C_{10} • 1,17.

3.3.5 *Capacidad útil*

Capacidad disponible o utilizable de la batería. Se define como el producto de la capacidad nominal y la profundidad máxima de descarga permitida, PD_{max}.

3.3.6 *Estado de carga*

Cociente entre la capacidad residual de una batería, en general parcialmente descargada, y su capacidad nominal.

3.3.7 *Profundidad de descarga (PD)*

Cociente entre la carga extraída de una batería y su capacidad nominal. Se expresa habitualmente en %.

3.3.8 *Régimen de carga* (*o descarga*)

Parámetro que relaciona la capacidad nominal de la batería y el valor de la corriente a la cual se realiza la carga (o la descarga). Se expresa normalmente en horas, y se representa como un subíndice en el símbolo de la capacidad y de la corriente a la cuál se realiza la carga (o la descarga). Por ejemplo, si una batería de 100 Ah se descarga en 20 horas a una corriente de 5 A, se dice que el régimen de descarga es 20 horas (C_{20} = 100 Ah) y la corriente se expresa como I_{20} =5 A.

3.3.9 *Vaso*

Elemento o celda electroquímica básica que forma parte de la batería, y cuya tensión nominal es aproximadamente 2 V.

3.4 Reguladores de carga

3.4.1 *Regulador de carga*

Dispositivo encargado de proteger a la batería frente a sobrecargas y sobredescargas. El regulador podrá no incluir alguna de estas funciones si existe otro componente del sistema encargado de realizarlas.

3.4.2 *Voltaje de desconexión de las cargas de consumo*

Voltaje de la batería por debajo del cual se interrumpe el suministro de electricidad a las cargas de consumo.

3.4.3 *Voltaje final de carga*

Voltaje de la batería por encima del cual se interrumpe la conexión entre el generador fotovoltaico y la batería, o reduce gradualmente la corriente media entregada por el generador fotovoltaico.

3.5 Inversores

3.5.1 *Inversor*

Convertidor de corriente continua en corriente alterna.

3.5.2 V_{RMS}

Valor eficaz de la tensión alterna de salida.

3.5.3 *Potencia nominal* (VA)

Potencia especificada por el fabricante, y que el inversor es capaz de entregar de forma continua.

3.5.4 *Capacidad de sobrecarga*

Capacidad del inversor para entregar mayor potencia que la nominal durante ciertos intervalos de tiempo.

3.5.5 *Rendimiento del inversor*

Relación entre la potencia de salida y la potencia de entrada del inversor. Depende de la potencia y de la temperatura de operación.

3.5.6 *Factor de potencia*

Cociente entre la potencia activa (W) y la potencia aparente (VA) a la salida del inversor.

3.5.7 *Distorsión armónica total*: THD (%)

Parámetro utilizado para indicar el contenido armónico de la onda de tensión de salida. Se define como:

$$THD\,(\%) = 100\,\frac{\sqrt{\sum_{n=2}^{n=\infty} V_n^2}}{V_1}$$

donde V_1 es el armónico fundamental y V_n el armónico enésimo.

3.6 Cargas de consumo

3.6.1 *Lámpara fluorescente de corriente continua*

Conjunto formado por un balastro y un tubo fluorescente

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4. Diseño

4.1 Orientación, inclinación y sombras

4.1.1 Las pérdidas de radiación causadas por una orientación e inclinación del generador distintas a las óptimas, y por sombreado, en el período de diseño, no serán superiores a los valores especificados en la tabla I.

Tabla I

Pérdidas de radiación del generador	*Valor máximo permitido* (%)
Inclinación y orientación	20
Sombras	10
Combinación de ambas	20

4.1.2 El cálculo de las pérdidas de radiación causadas por una inclinación y orientación del generador distintas a las óptimas se hará de acuerdo al apartado 3.2 del anexo I.

4.1.3 En aquellos casos en los que, por razones justificadas, no se verifiquen las condiciones del apartado 4.1.1, se evaluarán las pérdidas totales de radiación, incluyéndose el cálculo en la Memoria de Solicitud.

4.2 Dimensionado del sistema

4.2.1 Independientemente del método de dimensionado utilizado por el instalador, deberán realizarse los cálculos mínimos justificativos que se especifican en este PCT.

4.2.2 Se realizará una estimación del consumo de energía de acuerdo con el primer apartado del anexo I.

4.2.3 Se determinará el rendimiento energético de la instalación y el generador mínimo requerido ($P_{\mathrm{mp,\,min}}$) para cubrir las necesidades de consumo según lo estipulado en el anexo I, apartado 3.4.

4.2.4 El instalador podrá elegir el tamaño del generador y del acumulador en función de las necesidades de autonomía del sistema, de la probabilidad de pérdida de carga requerida y de cualquier otro factor que quiera considerar. El tamaño del generador será, como máximo, un 20 % superior al $P_{\mathrm{mp,\,min}}$ calculado en 4.2.3. En aplicaciones especiales en las que se requieran probabilidades de pérdidas de carga muy pequeñas podrá aumentarse el tamaño del generador, justificando la necesidad y el tamaño en la Memoria de Solicitud.

4.2.5 Como norma general, la autonomía mínima de sistemas con acumulador será de tres días. Se calculará la autonomía del sistema para el acumulador elegido (conforme a la expresión del apartado 3.5 del anexo I). En aplicaciones especiales, instalaciones mixtas eólico-fotovoltaicas, instalaciones con cargador de baterías o grupo electrógeno de apoyo, etc. que no cumplan este requisito se justificará adecuadamente.

4.2.6 Como criterio general, se valorará especialmente el aprovechamiento energético de la radiación solar.

4.3 Sistema de monitorización

4.3.1 El sistema de monitorización, cuando se instale, proporcionará medidas, como mínimo, de las siguientes variables:

- Tensión y corriente CC del generador.
- Potencia CC consumida, incluyendo el inversor como carga CC.
- Potencia CA consumida si la hubiere, salvo para instalaciones cuya aplicación es exclusivamente el bombeo de agua.
- Contador volumétrico de agua para instalaciones de bombeo.
- Radiación solar en el plano de los módulos medida con un módulo o una célula de tecnología equivalente.
- Temperatura ambiente en la sombra.

4.3.2 Los datos se presentarán en forma de medias horarias. Los tiempos de adquisición, la precisión de las medidas y el formato de presentación de las mismas se hará conforme al documento del JRC-Ispra "Guidelines for the Assessment of Photovoltaic Plants – Document A", Report EUR 16338 EN.

5. Componentes y materiales

5.1 Generalidades

5.1.1 Todas las instalaciones deberán cumplir con las exigencias de protecciones y seguridad de las personas, y entre ellas las dispuestas en el Reglamento Electrotécnico de Baja Tensión o legislación posterior vigente.

5.1.2 Como principio general, se tiene que asegurar, como mínimo, un grado de aislamiento eléctrico de tipo básico (clase I) para equipos y materiales.

5.1.3 Se incluirán todos los elementos necesarios de seguridad para proteger a las personas frente a contactos directos e indirectos, especialmente en instalaciones con tensiones de operación superiores a 50 V_{RMS} o 120 V_{CC}. Se recomienda la utilización de equipos y materiales de aislamiento eléctrico de clase II.

5.1.4 Se incluirán todas las protecciones necesarias para proteger a la instalación frente a cortocircuitos, sobrecargas y sobretensiones.

5.1.5 Los materiales situados en intemperie se protegerán contra los agentes ambientales, en particular contra el efecto de la radiación solar y la humedad. Todos los equipos expuestos a la intemperie tendrán un grado mínimo de protección IP65, y los de interior, IP20.

5.1.6 Los equipos electrónicos de la instalación cumplirán con las directivas comunitarias de Seguridad Eléctrica y Compatibilidad Electromagnética (ambas podrán ser certificadas por el fabricante).

5.1.7 Se incluirá en la Memoria toda la información requerida en el anexo II.

5.1.8 En la Memoria de Diseño o Proyecto se incluirá toda la información del apartado 5.1.7, resaltando los cambios que hubieran podido producirse y el motivo de los mismos. En la Memoria de Diseño o Proyecto también se incluirán las especificaciones técnicas, proporcionadas por el fabricante, de todos los elementos de la instalación.

5.1.9 Por motivos de seguridad y operación de los equipos, los indicadores, etiquetas, etc. de los mismos estarán en alguna de las lenguas españolas oficiales del lugar donde se sitúa la instalación.

5.2 Generadores fotovoltaicos

5.2.1 Todos los módulos deberán satisfacer las especificaciones UNE-EN 61215 para módulos de silicio cristalino, UNE-EN 61646 para módulos fotovoltaicos de capa delgada, o UNE-EN 62108 para módulos de concentración, así como la especificación UNE-EN 61730-1 y 2 sobre seguridad en módulos FV, Este requisito se justificará mediante la presentación del certificado oficial correspondiente emitido por algún laboratorio acreditado.

5.2.2 El módulo llevará de forma claramente visible e indeleble el modelo, nombre o logotipo del fabricante, y el número de serie, trazable a la fecha de fabricación, que permita su identificación individual.

5.2.3 Se utilizarán módulos que se ajusten a las características técnicas descritas a continuación. En caso de variaciones respecto de estas características, con carácter excepcional, deberá presentarse en la Memoria justificación de su utilización.

5.2.3.1 Los módulos deberán llevar los diodos de derivación para evitar las posibles averías de las células y sus circuitos por sombreados parciales, y tendrán un grado de protección IP65.

5.2.3.2 Los marcos laterales, si existen, serán de aluminio o acero inoxidable.

5.2.3.3 Para que un módulo resulte aceptable, su potencia máxima y corriente de cortocircuito reales, referidas a condiciones estándar deberán estar comprendidas en el margen del ± 5 % de los correspondientes valores nominales de catálogo.

5.2.3.4 Será rechazado cualquier módulo que presente defectos de fabricación, como roturas o manchas en cualquiera de sus elementos así como falta de alineación en las células, o burbujas en el encapsulante.

5.2.4 Cuando las tensiones nominales en continua sean superiores a 48 V, la estructura del generador y los marcos metálicos de los módulos estarán conectados a una toma de tierra, que será la misma que la del resto de la instalación.

5.2.5 Se instalarán los elementos necesarios para la desconexión, de forma independiente y en ambos terminales, de cada una de las ramas del generador.

5.2.6 En aquellos casos en que se utilicen módulos no cualificados, deberá justificarse debidamente y aportar documentación sobre las pruebas y ensayos a los que han sido sometidos. En cualquier caso, todo producto que no cumpla alguna de las especificaciones anteriores deberá contar con la aprobación expresa del IDAE. En todos los casos han de cumplirse las normas vigentes de obligado cumplimiento.

5.3 Estructura de soporte

5.3.1 Se dispondrán las estructuras soporte necesarias para montar los módulos y se incluirán todos los accesorios que se precisen.

5.3.2 La estructura de soporte y el sistema de fijación de módulos permitirán las necesarias dilataciones térmicas sin transmitir cargas que puedan afectar a la integridad de los módulos, siguiendo las normas del fabricante.

5.3.3 La estructura soporte de los módulos ha de resistir, con los módulos instalados, las sobrecargas del viento y nieve, de acuerdo con lo indicado en el Código Técnico de la Edificación (CTE).

5.3.4 El diseño de la estructura se realizará para la orientación y el ángulo de inclinación especificado para el generador fotovoltaico, teniendo en cuenta la facilidad de montaje y desmontaje, y la posible necesidad de sustituciones de elementos.

5.3.5 La estructura se protegerá superficialmente contra la acción de los agentes ambientales. La realización de taladros en la estructura se llevará a cabo antes de proceder, en su caso, al galvanizado o protección de la misma.

5.3.6 La tornillería empleada deberá ser de acero inoxidable. En el caso de que la estructura sea galvanizada se admitirán tornillos galvanizados, exceptuando los de sujeción de los módulos a la misma, que serán de acero inoxidable.

5.3.7 Los topes de sujeción de módulos, y la propia estructura, no arrojarán sombra sobre los módulos.

5.3.8 En el caso de instalaciones integradas en cubierta que hagan las veces de la cubierta del edificio, el diseño de la estructura y la estanquidad entre módulos se ajustará a las exigencias del Código Técnico de la Edificación y a las técnicas usuales en la construcción de cubiertas.

5.3.9 Si está construida con perfiles de acero laminado conformado en frío, cumplirá la Norma MV102 para garantizar todas sus características mecánicas y de composición química.

5.3.10 Si es del tipo galvanizada en caliente, cumplirá las Normas UNE 37-501 y UNE 37-508, con un espesor mínimo de 80 micras, para eliminar las necesidades de mantenimiento y prolongar su vida útil.

5.4 Acumuladores de plomo-ácido

5.4.1 Se recomienda que los acumuladores sean de plomo-ácido, preferentemente estacionarias y de placa tubular. No se permitirá el uso de baterías de arranque.

5.4.2 Para asegurar una adecuada recarga de las baterías, la capacidad nominal del acumulador (en Ah) no excederá en 25 veces la corriente (en A) de cortocircuito en CEM del generador fotovoltaico. En el caso de que la capacidad del acumulador elegido sea superior a este valor (por existir el apoyo de un generador eólico, cargador de baterías, grupo electrógeno, etc.), se justificará adecuadamente.

5.4.3 La máxima profundidad de descarga (referida a la capacidad nominal del acumulador) no excederá el 80 % en instalaciones donde se prevea que descargas tan profundas no serán frecuentes. En aquellas aplicaciones en las que estas sobredescargas puedan ser habituales, tales como alumbrado público, la máxima profundidad de descarga no superará el 60 %.

5.4.4 Se protegerá, especialmente frente a sobrecargas, a las baterías con electrolito gelificado, de acuerdo a las recomendaciones del fabricante.

5.4.5 La capacidad inicial del acumulador será superior al 90 % de la capacidad nominal. En cualquier caso, deberán seguirse las recomendaciones del fabricante para aquellas baterías que requieran una carga inicial.

5.4.6 La autodescarga del acumulador a 20°C no excederá el 6% de su capacidad nominal por mes.

5.4.7 La vida del acumulador, definida como la correspondiente hasta que su capacidad residual caiga por debajo del 80 % de su capacidad nominal, debe ser superior a 1000 ciclos, cuando se descarga el acumulador hasta una profundidad del 50 % a 20 °C.

5.4.8 El acumulador será instalado siguiendo las recomendaciones del fabricante. En cualquier caso, deberá asegurarse lo siguiente:

- El acumulador se situará en un lugar ventilado y con acceso restringido.
- Se adoptarán las medidas de protección necesarias para evitar el cortocircuito accidental de los terminales del acumulador, por ejemplo, mediante cubiertas aislantes.

5.4.9 Cada batería, o vaso, deberá estar etiquetado, al menos, con la siguiente información:

- Tensión nominal (V)
- Polaridad de los terminales

- Capacidad nominal (Ah)
- Fabricante (nombre o logotipo) y número de serie

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5.5 Reguladores de carga

5.5.1 Las baterías se protegerán contra sobrecargas y sobredescargas. En general, estas protecciones serán realizadas por el regulador de carga, aunque dichas funciones podrán incorporarse en otros equipos siempre que se asegure una protección equivalente.

5.5.2 Los reguladores de carga que utilicen la tensión del acumulador como referencia para la regulación deberán cumplir los siguientes requisitos:

- La tensión de desconexión de la carga de consumo del regulador deberá elegirse para que la interrupción del suministro de electricidad a las cargas se produzca cuando el acumulador haya alcanzado la profundidad máxima de descarga permitida (ver 5.4.3). La precisión en las tensiones de corte efectivas respecto a los valores fijados en el regulador será del 1 %.
- La tensión final de carga debe asegurar la correcta carga de la batería.
- La tensión final de carga debe corregirse por temperatura a razón de –4mV/°C a –5 mV/°C por vaso, y estar en el intervalo de ± 1 % del valor especificado.
- Se permitirán sobrecargas controladas del acumulador para evitar la estratificación del electrolito o para realizar cargas de igualación.

5.5.3 Se permitirá el uso de otros reguladores que utilicen diferentes estrategias de regulación atendiendo a otros parámetros, como por ejemplo, el estado de carga del acumulador. En cualquier caso, deberá asegurarse una protección equivalente del acumulador contra sobrecargas y sobredescargas.

5.5.4 Los reguladores de carga estarán protegidos frente a cortocircuitos en la línea de consumo.

5.5.5 El regulador de carga se seleccionará para que sea capaz de resistir sin daño una sobrecarga simultánea, a la temperatura ambiente máxima, de:

- Corriente en la línea de generador: un 25% superior a la corriente de cortocircuito del generador fotovoltaico en CEM.
- Corriente en la línea de consumo: un 25 % superior a la corriente máxima de la carga de consumo.

5.5.6 El regulador de carga debería estar protegido contra la posibilidad de desconexión accidental del acumulador, con el generador operando en las CEM y con cualquier carga. En estas condiciones, el regulador debería asegurar, además de su propia protección, la de las cargas conectadas.

5.5.7 Las caídas internas de tensión del regulador entre sus terminales de generador y acumulador serán inferiores al 4% de la tensión nominal (0,5 V para 12 V de tensión nominal), para sistemas de menos de 1 kW, y del 2% de la tensión nominal para sistemas mayores de 1 kW, incluyendo

los terminales. Estos valores se especifican para las siguientes condiciones: corriente nula en la línea de consumo y corriente en la línea generador-acumulador igual a la corriente máxima especificada para el regulador. Si las caídas de tensión son superiores, por ejemplo, si el regulador incorpora un diodo de bloqueo, se justificará el motivo en la Memoria de Solicitud.

5.5.8 Las caídas internas de tensión del regulador entre sus terminales de batería y consumo serán inferiores al 4% de la tensión nominal (0,5 V para 12 V de tensión nominal), para sistemas de menos de 1 kW, y del 2 % de la tensión nominal para sistemas mayores de 1 kW, incluyendo los terminales. Estos valores se especifican para las siguientes condiciones: corriente nula en la línea de generador y corriente en la línea acumulador-consumo igual a la corriente máxima especificada para el regulador.

5.5.9 Las pérdidas de energía diarias causadas por el autoconsumo del regulador en condiciones normales de operación deben ser inferiores al 3 % del consumo diario de energía.

5.5.10 Las tensiones de reconexión de sobrecarga y sobredescarga serán distintas de las de desconexión, o bien estarán temporizadas, para evitar oscilaciones desconexión-reconexión.

5.5.11 El regulador de carga deberá estar etiquetado con al menos la siguiente información:

- Tensión nominal (V)
- Corriente máxima (A)
- Fabricante (nombre o logotipo) y número de serie
- Polaridad de terminales y conexiones

5.6 Inversores

5.6.1 Los requisitos técnicos de este apartado se aplican a inversores monofásicos o trifásicos que funcionan como fuente de tensión fija (valor eficaz de la tensión y frecuencia de salida fijos). Para otros tipos de inversores se asegurarán requisitos de calidad equivalentes.

5.6.2 Los inversores serán de onda senoidal pura. Se permitirá el uso de inversores de onda no senoidal, si su potencia nominal es inferior a 1 kVA, no producen daño a las cargas y aseguran una correcta operación de éstas.

5.6.3 Los inversores se conectarán a la salida de consumo del regulador de carga o en bornes del acumulador. En este último caso se asegurará la protección del acumulador frente a sobrecargas y sobredescargas, de acuerdo con lo especificado en el apartado 5.4. Estas protecciones podrán estar incorporadas en el propio inversor o se realizarán con un regulador de carga, en cuyo caso el regulador debe permitir breves bajadas de tensión en el acumulador para asegurar el arranque del inversor.

5.6.4 El inversor debe asegurar una correcta operación en todo el margen de tensiones de entrada permitidas por el sistema.

5.6.5 La regulación del inversor debe asegurar que la tensión y la frecuencia de salida estén en los siguientes márgenes, en cualquier condición de operación:

V_{NOM} ± 5 %, siendo V_{NOM} = 220 V_{RMS} o 230 V_{RMS} 50 Hz ± 2%

5.6.6 El inversor será capaz de entregar la potencia nominal de forma continuada, en el margen de temperatura ambiente especificado por el fabricante.

5.6.7 El inversor debe arrancar y operar todas las cargas especificadas en la instalación, especialmente aquellas que requieren elevadas corrientes de arranque (TV, motores, etc.), sin interferir en su correcta operación ni en el resto de cargas.

5.6.8 Los inversores estarán protegidos frente a las siguientes situaciones:

- Tensión de entrada fuera del margen de operación.
- Desconexión del acumulador.
- Cortocircuito en la salida de corriente alterna.
- Sobrecargas que excedan la duración y límites permitidos.

5.6.9 El autoconsumo del inversor sin carga conectada será menor o igual al 2 % de la potencia nominal de salida.

5.6.10 Las pérdidas de energía diaria ocasionadas por el autoconsumo del inversor serán inferiores al 5 % del consumo diario de energía. Se recomienda que el inversor tenga un sistema de "stand-by" para reducir estas pérdidas cuando el inversor trabaja en vacío (sin carga).

5.6.11 El rendimiento del inversor con cargas resistivas será superior a los límites especificados en la tabla II.

Tabla II

Tipo de inversor		*Rendimiento al 20 % de la potencia nominal*	*Rendimiento a potencia nominal*
Onda senoidal (*)	P_{NOM} # 500 VA	> 85 %	> 75 %

	P_{NOM} > 500 VA	> 90 %	> 85 %
Onda no senoidal		> 90 %	> 85 %

(*) Se considerará que los inversores son de onda senoidal si la distorsión armónica total de la tensión de salida es inferior al 5% cuando el inversor alimenta cargas lineales, desde el 20 % hasta el 100 % de la potencia nominal.

5.6.12 Los inversores deberán estar etiquetados con, al menos, la siguiente información:

- Potencia nominal (VA)
- Tensión nominal de entrada (V)
- Tensión (V_{RMS}) y frecuencia (Hz) nominales de salida
- Fabricante (nombre o logotipo) y número de serie
- Polaridad y terminales

5.7 Cargas de consumo

5.7.1 Se recomienda utilizar electrodomésticos de alta eficiencia.

5.7.2 Se utilizarán lámparas fluorescentes, preferiblemente de alta eficiencia. No se permitirá el uso de lámparas incandescentes.

5.7.3 Las lámparas fluorescentes de corriente alterna deberán cumplir la normativa al respecto. Se recomienda utilizar lámparas que tengan corregido el factor de potencia.

5.7.4 En ausencia de un procedimiento reconocido de cualificación de lámparas fluorescentes de continua, estos dispositivos deberán verificar los siguientes requisitos:

- El balastro debe asegurar un encendido seguro en el margen de tensiones de operación, y en todo el margen de temperaturas ambientes previstas.
- La lámpara debe estar protegida cuando:
- Se invierte la polaridad de la tensión de entrada.
- La salida del balastro es cortocircuitada.
- Opera sin tubo.
- La potencia de entrada de la lámpara debe estar en el margen de ±10% de la potencia nominal.
- El rendimiento luminoso de la lámpara debe ser superior a 40 lúmenes/W.
- La lámpara debe tener una duración mínima de 5000 ciclos cuando se aplica el siguiente ciclado: 60 segundos encendido /150 segundos apagado, y a una temperatura de 20 °C.
- Las lámparas deben cumplir las directivas europeas de seguridad eléctrica y compatibilidad electromagnética.

5.7.5 Se recomienda que no se utilicen cargas para climatización.

5.7.6 Los sistemas con generadores fotovoltaicos de potencia nominal superior a 500 W tendrán, como mínimo, un contador para medir el consumo de energía (excepto sistemas de bombeo). En sistemas mixtos con consumos en continua y alterna, bastará un contador para medir el consumo en continua de las cargas CC y del inversor. En sistemas con consumos de corriente alterna únicamente, se colocará el contador a la salida del inversor.

5.7.7 Los enchufes y tomas de corriente para corriente continua deben estar protegidos contra inversión de polaridad y ser distintos de los de uso habitual para corriente alterna.

5.7.8 Para sistemas de bombeo de agua:

5.7.8.1 Los sistemas de bombeo con generadores fotovoltaicos de potencia nominal superior a 500 W tendrán un contador volumétrico para medir el volumen de agua bombeada.

5.7.8.2 Las bombas estarán protegidas frente a una posible falta de agua, ya sea mediante un sistema de detección de la velocidad de giro de la bomba, un detector de nivel u otro dispositivo dedicado a tal función.

5.7.8.3 Las pérdidas por fricción en las tuberías y en otros accesorios del sistema hidráulico serán inferiores al 10% de la energía hidráulica útil proporcionada por la motobomba.

5.7.8.4 Deberá asegurarse la compatibilidad entre la bomba y el pozo. En particular, el caudal bombeado no excederá el caudal máximo extraible del pozo cuando el generador fotovoltaico trabaja en CEM. Es responsabilidad del instalador solicitar al propietario del pozo un estudio de caracterización del mismo. En ausencia de otros procedimientos se puede seguir el que se especifica en el anexo I.

5.8 Cableado

5.8.1 Todo el cableado cumplirá con lo establecido en la legislación vigente.

5.8.2 Los conductores necesarios tendrán la sección adecuada para reducir las caídas de tensión y los calentamientos. Concretamente, para cualquier condición de trabajo, los conductores deberán tener la sección suficiente para que la caída de tensión sea inferior, incluyendo cualquier terminal intermedio, al 1,5 % a la tensión nominal continua del sistema.

5.8.3 Se incluirá toda la longitud de cables necesaria (parte continua y/o alterna) para cada aplicación concreta, evitando esfuerzos sobre los elementos de la instalación y sobre los propios cables.

5.8.4 Los positivos y negativos de la parte continua de la instalación se conducirán separados, protegidos y señalizados (códigos de colores, etiquetas, etc.) de acuerdo a la normativa vigente.

5.8.5 Los cables de exterior estarán protegidos contra la intemperie.

5.9 Protecciones y puesta a tierra

5.9.1 Todas las instalaciones con tensiones nominales superiores a 48 voltios contarán con una toma de tierra a la que estará conectada, como mínimo, la estructura soporte del generador y los marcos metálicos de los módulos.

5.9.2 El sistema de protecciones asegurará la protección de las personas frente a contactos directos e indirectos. En caso de existir una instalación previa no se alterarán las condiciones de seguridad de la misma.

5.9.3 La instalación estará protegida frente a cortocircuitos, sobrecargas y sobretensiones. Se prestará especial atención a la protección de la batería frente a cortocircuitos mediante un fusible, disyuntor magnetotérmico u otro elemento que cumpla con esta función.

6. Recepción y pruebas

6.1 El instalador entregará al usuario un documento-albarán en el que conste el suministro de componentes, materiales y manuales de uso y mantenimiento de la instalación. Este documento será firmado por duplicado por ambas partes, conservando cada una un ejemplar. Los manuales entregados al usuario estarán en alguna de las lenguas oficiales españolas del lugar del usuario de la instalación, para facilitar su correcta interpretación.

6.2 Las pruebas a realizar por el instalador, con independencia de lo indicado con anterioridad en este PCT, serán, como mínimo, las siguientes:

6.2.1 Funcionamiento y puesta en marcha del sistema.

6.2.2 Prueba de las protecciones del sistema y de las medidas de seguridad, especialmente las del acumulador.

6.3 Concluidas las pruebas y la puesta en marcha se pasará a la fase de la Recepción Provisional de la Instalación. El Acta de Recepción Provisional no se firmará hasta haber comprobado que el sistema ha funcionado correctamente durante un mínimo de 240 horas seguidas, sin interrupciones o paradas causadas por fallos del sistema suministrado. Además se deben cumplir los siguientes requisitos:

6.3.1 Entrega de la documentación requerida en este PCT.

6.3.2 Retirada de obra de todo el material sobrante.

6.3.3 Limpieza de las zonas ocupadas, con transporte de todos los desechos a vertedero.

6.4 Durante este período el suministrador será el único responsable de la operación del sistema, aunque deberá adiestrar al usuario.

6.5 Todos los elementos suministrados, así como la instalación en su conjunto, estarán protegidos frente a defectos de fabricación, instalación o elección de componentes por una garantía de tres años, salvo para los módulos fotovoltaicos, para los que la garantía será de ocho años contados a partir de la fecha de la firma del Acta de Recepción Provisional.

6.6 No obstante, vencida la garantía, el instalador quedará obligado a la reparación de los fallos de funcionamiento que se puedan producir si se apreciase que su origen procede de defectos ocultos de diseño, construcción, materiales o montaje, comprometiéndose a subsanarlos sin cargo alguno. En cualquier caso, deberá atenerse a lo establecido en la legislación vigente en cuanto a vicios ocultos.

7 Requerimientos técnicos del contrato de mantenimiento

7.1 Generalidades

7.1.1 Se realizará un contrato de mantenimiento (preventivo y correctivo), al menos, de tres años.

7.1.2 El mantenimiento preventivo implicará, como mínimo, una revisión anual.

7.1.3 El contrato de mantenimiento de la instalación incluirá las labores de mantenimiento de todos los elementos de la instalación aconsejados por los diferentes fabricantes.

7.2 Programa de mantenimiento

7.2.1 El objeto de este apartado es definir las condiciones generales mínimas que deben seguirse para el mantenimiento de las instalaciones de energía solar fotovoltaica aisladas de la red de distribución eléctrica.

7.2.2 Se definen dos escalones de actuación para englobar todas las operaciones necesarias durante la vida útil de la instalación, para asegurar el funcionamiento, aumentar la producción y prolongar la duración de la misma:

- Mantenimiento preventivo
- Mantenimiento correctivo

7.2.3 Plan de mantenimiento preventivo: operaciones de inspección visual, verificación de actuaciones y otras, que aplicadas a la instalación deben permitir mantener, dentro de límites aceptables, las condiciones de funcionamiento, prestaciones, protección y durabilidad de la instalación.

7.2.4 Plan de mantenimiento correctivo: todas las operaciones de sustitución necesarias para asegurar que el sistema funciona correctamente durante su vida útil. Incluye:

- La visita a la instalación en los plazos indicados en el apartado 7.3.5.2, y cada vez que el usuario lo requiera por avería grave en la instalación.
- El análisis y presupuestación de los trabajos y reposiciones necesarias para el correcto funcionamiento de la misma.
- Los costes económicos del mantenimiento correctivo, con el alcance indicado, forman parte del precio anual del contrato de mantenimiento. Podrán no estar incluidas ni la mano de obra, ni las reposiciones de equipos necesarias más allá del período de garantía.

7.2.5 El mantenimiento debe realizarse por personal técnico cualificado bajo la responsabilidad de la empresa instaladora.

7.2.6 El mantenimiento preventivo de la instalación incluirá una visita anual en la que se realizarán, como mínimo, las siguientes actividades:

- Verificación del funcionamiento de todos los componentes y equipos.
- Revisión del cableado, conexiones, pletinas, terminales, etc.
- Comprobación del estado de los módulos: situación respecto al proyecto original, limpieza y presencia de daños que afecten a la seguridad y protecciones.
- Estructura soporte: revisión de daños en la estructura, deterioro por agentes ambientales, oxidación, etc.
- Baterías: nivel del electrolito, limpieza y engrasado de terminales, etc.
- Regulador de carga: caídas de tensión entre terminales, funcionamiento de indicadores, etc.
- Inversores: estado de indicadores y alarmas.
- Caídas de tensión en el cableado de continua.
- Verificación de los elementos de seguridad y protecciones: tomas de tierra, actuación de interruptores de seguridad, fusibles, etc.

7.2.7 En instalaciones con monitorización la empresa instaladora de la misma realizará una revisión cada seis meses, comprobando la calibración y limpieza de los medidores, funcionamiento y calibración del sistema de adquisición de datos, almacenamiento de los datos, etc.

7.2.8 Las operaciones de mantenimiento realizadas se registrarán en un libro de mantenimiento.

7.3 Garantías

7.3.1 Ámbito general de la garantía:

7.3.1.1 Sin perjuicio de una posible reclamación a terceros, la instalación será reparada de acuerdo con estas condiciones generales si ha sufrido una avería a causa de un defecto de montaje o de cualquiera de los componentes, siempre que haya sido manipulada correctamente de acuerdo con lo establecido en el manual de instrucciones.

7.3.1.2 La garantía se concede a favor del comprador de la instalación, lo que deberá justificarse debidamente mediante el correspondiente certificado de garantía, con la fecha que se acredite en la entrega de la instalación.

7.3.2 Plazos:

7.3.2.1 El suministrador garantizará la instalación durante un período mínimo de tres años, para todos los materiales utilizados y el montaje. Para los módulos fotovoltaicos, la garantía será de ocho años.

7.3.2.2 Si hubiera de interrumpirse la explotación del sistema debido a razones de las que es responsable el suministrador, o a reparaciones que haya de realizar para cumplir las estipulaciones de la garantía, el plazo se prolongará por la duración total de dichas interrupciones.

7.3.3 Condiciones económicas:

7.3.3.1 La garantía incluye tanto la reparación o reposición de los componentes y las piezas que pudieran resultar defectuosas, como la mano de obra.

7.3.3.2 Quedan incluidos los siguientes gastos: tiempos de desplazamiento, medios de transporte, amortización de vehículos y herramientas, disponibilidad de otros medios y eventuales portes de recogida y devolución de los equipos para su reparación en los talleres del fabricante.

7.3.3.3 Asimismo, se debe incluir la mano de obra y materiales necesarios para efectuar los ajustes y eventuales reglajes del funcionamiento de la instalación.

7.3.3.4 Si, en un plazo razonable, el suministrador incumple las obligaciones derivadas de la garantía, el comprador de la instalación podrá, previa notificación escrita, fijar una fecha final para que dicho suministrador cumpla con sus obligaciones. Si el suministrador no cumple con sus obligaciones en dicho plazo último, el comprador de la instalación podrá, por cuenta y riesgo del suministrador, realizar por sí mismo las oportunas reparaciones, o contratar para ello a un tercero, sin perjuicio de la reclamación por daños y perjuicios en que hubiere incurrido el suministrador.

7.3.4 Anulación de la garantía:

7.3.4.1 La garantía podrá anularse cuando la instalación haya sido reparada, modificada o desmontada, aunque sólo sea en parte, por personas ajenas al suministrador o a los servicios de asistencia técnica de los fabricantes no autorizados expresamente por el suministrador, excepto en las condiciones del último punto del apartado 7.3.3.4.

7.3.5 Lugar y tiempo de la prestación:

7.3.5.1 Cuando el usuario detecte un defecto de funcionamiento en la instalación lo comunicará fehacientemente al suministrador. Cuando el suministrador considere que es un defecto de fabricación de algún componente lo comunicará fehacientemente al fabricante.

7.3.5.2 El suministrador atenderá el aviso en un plazo máximo de 48 horas si la instalación no funciona, o de una semana si el fallo no afecta al funcionamiento.

7.3.5.3 Las averías de las instalaciones se repararán en su lugar de ubicación por el suministrador. Si la avería de algún componente no pudiera ser reparada en el domicilio del usuario, el componente deberá ser enviado al taller oficial designado por el fabricante por cuenta y a cargo del suministrador.

7.3.5.4 El suministrador realizará las reparaciones o reposiciones de piezas con la mayor brevedad posible una vez recibido el aviso de avería, pero no se responsabilizará de los perjuicios causados por la demora en dichas reparaciones siempre que sea inferior a 15 días naturales.

ANEXO I

DIMENSIONADO DEL SISTEMA FOTOVOLTAICO

I. Estimación del consumo diario de energía

1 Generalidades:

1.1 La estimación correcta de la energía consumida por el sistema fotovoltaico sólo es sencilla en aquellas aplicaciones en las que se conocen exactamente las características de la carga (por ejemplo, sistemas de telecomunicación). Sin embargo, en otras aplicaciones, como puede ser la electrificación de viviendas, la tarea no resulta fácil pues intervienen multitud de factores que afectan al consumo final de electricidad: tamaño y composición de las familias (edad, formación, etc.), hábitos de los usuarios, capacidad para administrar la energía disponible, etc.

1.2 El objeto de este apartado es estimar la energía media diaria consumida por el sistema, E_D (Wh/día).

1.3 El cálculo de la energía consumida incluirá las pérdidas diarias de energía causadas por el autoconsumo de los equipos (regulador, inversor, etc.).

1.4 El consumo de energía de las cargas incluirá el servicio de energía eléctrica ofrecido al usuario para distintas aplicaciones (iluminación, TV, frigorífico, bombeo de agua, etc.).

1.5 Para propósitos de dimensionado del acumulador, se calculará el consumo medio diario en Ah/día, L_D, como:

$$L_D\,(\text{Ah/día}) = \frac{E_D\,(\text{Wh/día})}{V_{NOM}\,(\text{V})}$$

donde V_{NOM} (V) es la tensión nominal del acumulador.

1.6 Los parámetros requeridos en la Memoria de Solicitud para una aplicación destinada al bombeo de agua serán calculados por el instalador usando los métodos y herramientas que estime oportunos. En su defecto, el apartado 2 describe un procedimiento aproximado de cálculo que permite considerar las características dinámicas del pozo.

2 Bombeo de agua:

2.1 Definiciones

2.1.1 *Altura de fricción*: H_f (m).

Contribución equivalente en altura de las pérdidas por fricción en las tuberías para un caudal determinado.

2.1.2 *Altura del depósito*: H_D (m).

Altura entre el depósito de agua y el suelo.

2.1.3 *Altura total equivalente*: H_{TE} (m).

Altura fija (constante ficticia) a la que se habría tenido que bombear el volumen diario de agua requerido.

2.1.4 *Volumen diario de agua requerido*: Q_d (m^3/día).

Cantidad de agua que debe ser bombeada diariamente por el sistema fotovoltaico.

2.1.5 *Caudal medio o aparente*: Q_{AP} (m^3/h).

Valor medio del volumen diario de agua requerido ($Q_{AP} = Q_d / 24$).

2.1.6 *Eficiencia de la motobomba*: η_{MB} .

Cociente entre la energía hidráulica y la energía eléctrica consumida por la motobomba.

2.1.7 *Energía eléctrica consumida por la motobomba*: E_{MB} (Wh/día).

2.1.8 *Energía hidráulica*: E_H (Wh/día).

Energía necesaria para bombear el volumen diario de agua requerido.

2.1.9 *Prueba de bombeo*.

Experimento que permite determinar el descenso de nivel de agua de un pozo al extraer un determinado caudal de prueba. Mediante este ensayo de bombeo se caracteriza el pozo con la medida de tres parámetros:

- *Nivel estático del agua*: H_{ST} (m).
  Distancia vertical entre el nivel del suelo y el nivel del agua antes de la prueba de bombeo.
- *Nivel dinámico del agua*: H_{DT} (m).
  Distancia vertical entre el nivel del suelo y el nivel final del agua después de la prueba de bombeo.
- *Caudal de prueba*: Q_T (m^3/ h).
  Caudal de agua extraído durante la prueba de bombeo.

2.2 Cálculo de la energía eléctrica requerida por la motobomba:

2.2.1 Se estimará la energía eléctrica consumida por la motobomba como:

$$E_{MB}(\text{Wh/día}) = \frac{E_H(\text{Wh/día})}{\eta_{MB}} = \frac{2{,}725\, Q_d(\text{m}^3/\text{día}) \cdot H_{TE}(\text{m})}{\eta_{MB}}$$

2.2.2 Para sistemas de bombeo de corriente alterna, la eficiencia de la motobomba es un parámetro que suele estar incluido en el rendimiento del conjunto inversor-motobomba. Habitualmente, el fabricante proporciona herramientas gráficas para el cálculo del rendimiento global del sistema, incluyendo el propio generador fotovoltaico. Por defecto, puede utilizarse un rendimiento típico $\eta_{MB} = 0{,}4$ para bombas superiores a 500 W.

2.2.3 La altura equivalente de bombeo, H_{TE}, es un parámetro ficticio que incluye las características físicas del pozo y del depósito, las pérdidas por fricción en las tuberías (contribución equivalente en altura) y la variación del nivel dinámico del agua durante el bombeo. Para su cálculo puede utilizarse la fórmula siguiente:

$$H_{TE} = H_D + H_{ST} + \left(\frac{H_{DT} - H_{ST}}{Q_T}\right) Q_{AP} + H_f$$

La suma de los dos primeros términos es la altura desde la salida de la bomba en el depósito hasta el nivel estático del agua (figura 3). El tercer término es una corrección para tener en cuenta el descenso de agua durante el bombeo y el cuarto es la contribución equivalente en altura de las pérdidas por fricción en las tuberías y en otros accesorios del sistema hidráulico (válvulas, codos, grifos, etc.). Estas pérdidas, de acuerdo con el PCT, serán inferiores al 10% de la energía hidráulica útil (es decir, $H_f < 0{,}1H_{TE}$).

II. Dimensionado del sistema

1 Generalidades

1.1 El objeto de este apartado es evaluar el dimensionado del generador fotovoltaico llevado a cabo por el instalador, con independencia de los métodos que el instalador utilice para esta tarea.

1.2 Para ello se le pedirá que indique la eficiencia energética esperada para la instalación.

2 Definiciones

2.1 *Ángulo de inclinación* \$.

Ángulo que forma la superficie de los módulos con el plano horizontal (figura 1). Su valor es 0° para módulos horizontales y 90° para verticales.

2.2 *Ángulo de azimut* ".

Ángulo entre la proyección sobre el plano horizontal de la normal a la superficie del módulo y el meridiano del lugar (figura 2). Valores típicos son 0° para módulos orientados al sur, –90° para módulos orientados al este y +90° para módulos orientados al oeste.

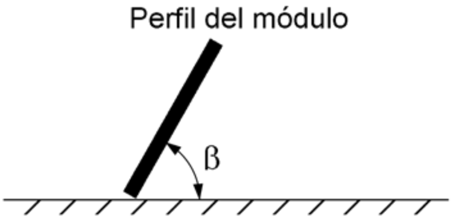

Fig. 1

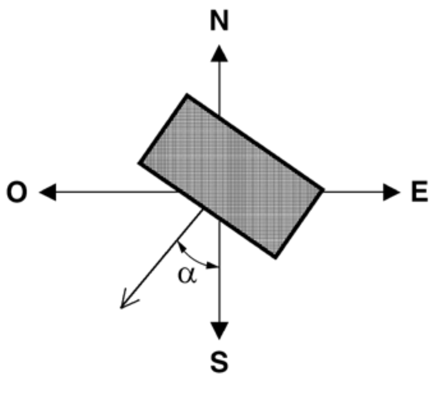

Fig. 2

2.3 G_{dm} (0).

Valor medio mensual o anual de la irradiación diaria sobre superficie horizontal en kWh/(m²Adía).

2.4 G_{dm} ("$_{opt}$, \$$_{opt}$). Valor medio mensual o anual de la irradiación diaria sobre el plano del generador orientado de forma óptima ("$_{opt}$, \$$_{opt}$), en kWh/(m² Adía). Se considera orientación óptima aquella que hace que la energía colectada sea máxima en un período.

2.5 G_{dm} (", \$).

Valor medio mensual de la irradiación diaria sobre el plano del generador en kWh/(m² Adía) y en el que se hayan descontado las pérdidas por sombreado.

2.6 *Factor de irradiación* (*FI*). Porcentaje de radiación incidente para un generador de orientación e inclinación (", $) respecto a la correspondiente para una orientación e inclinación óptimas (" = 0°, $\$_{opt}$). Las pérdidas de radiación respecto a la orientación e inclinación óptimas vienen dadas por (1 – *FI*).

2.7 *Factor de sombreado* (*FS*).

Porcentaje de radiación incidente sobre el generador respecto al caso de ausencia total de sombras. Las pérdidas por sombreado vienen dadas por (1 – *FS*).

2.8 *Rendimiento energético de la instalación o "performance ratio", PR.*

Eficiencia de la instalación en condiciones reales de trabajo para el período de diseño, de acuerdo con la ecuación:

$$PR = G_{dm} \overline{E\ G(_{D}\, \alpha\beta,\ _{CEM})}\ P_{mp}$$

G_{CEM} = 1 kW/m2

P_{mp}: Potencia pico del generador (kWp) E_D:
Consumo expresado en kWh/día.

Este factor considera las pérdidas en la eficiencia energética debido a:

- La temperatura.
- El cableado.
- Las pérdidas por dispersión de parámetros y suciedad.
- Las pérdidas por errores en el seguimiento del punto de máxima potencia.
- La eficiencia energética, O_{rb} , de otros elementos en operación como el regulador, batería, etc.
- La eficiencia energética del inversor, O_{inv}. – Otros.

Valores típicos son, en sistemas con inversor, *PR* ● 0,7 y, con inversor y batería, *PR* ● 0,6. A efectos de cálculo y por simplicidad, se utilizarán en sistemas con inversor *PR* = 0,7 y con inversor y batería *PR* = 0,6. Si se utilizase otro valor de *PR*, deberá justificarse el valor elegido desglosando los diferentes factores de pérdidas utilizados para su estimación.

En caso de acoplo directo de cargas al generador (por ejemplo, una bomba), se hará un cálculo justificativo de las pérdidas por desacoplo del punto de máxima potencia.

3 Procedimiento

3.1 Período de diseño

Se establecerá un período de diseño para calcular el dimensionado del generador en función de las necesidades de consumo y la radiación. Se indicará cuál es el período para el que se realiza el diseño y los motivos de la elección. Algunos ejemplos son:

- En escenarios de consumo constante a lo largo del año, el criterio de "mes peor" corresponde con el de menor radiación.
- En instalaciones de bombeo, dependiendo de la localidad y disponibilidad de agua, el "mes peor" corresponde a veces con el verano.

– Para maximizar la producción anual, el período de diseño es todo el año.

3.2 Orientación e inclinación óptimas. Pérdidas por orientación e inclinación Se determinará la orientación e inclinación óptimas (" = 0°, $\$_{opt}$) para el período de diseño elegido. En la tabla III se presentan períodos de diseño habituales y la correspondiente inclinación ($) del generador que hace que la colección de energía sea máxima.

Tabla III

Período de diseño	$\$_{opt}$	G (0 $K = _{dm}$ G α $_{dm}$ = ( ) 0
Diciembre	N + 10	1,7
Julio	N – 20	1
Anual	N – 10	1,15

N = Latitud del lugar en grados

El diseñador buscará, en la medida de lo posible, orientar el generador de forma que la energía captada sea máxima en el período de diseño (" = 0°, $\$_{opt}$). Sin embargo, no será siempre posible orientar e inclinar el generador de forma óptima, ya que pueden influir otros factores como son la acumulación de suciedad en los módulos, la resistencia al viento, las sombras, etc. Para calcular el factor de irradiación para la orientación e inclinación elegidas se utilizará la expresión aproximada:

$FI = 1 – [1,2×10^{–4} (\$ – \$_{opt})^2 + 3,5 × 10^{–5} "^2]$ para 15° < $ < 90°

$FI = 1 – [1,2×10^{–4} (\$ – \$_{opt})^2]$ para $ # 15°

[Nota: ", $ se expresan en grados]

3.3 Irradiación sobre el generador

Deberán presentarse los siguientes datos:

G_{dm} (0)

Obtenida a partir de alguna de las siguientes fuentes:

– Instituto Nacional de Meteorología
– Organismo autonómico oficial

G_{dm} (", $)

Calculado a partir de la expresión:

G_{dm} (", $) = G_{dm} (0) A K A FI A FS

donde:

$$K = \frac{G_{dm}(\alpha = 0, \beta_{opt})}{G_{dm}(\alpha, \beta)}$$

Este parámetro puede obtenerse de la tabla III para el período de diseño elegido.

3.4 Dimensionado del generador

El dimensionado mínimo del generador, en primera instancia, se realizará de acuerdo con los datos anteriores, según la expresión:

$$P_{mp,\,min} = \frac{E_D\, G_{CEM}}{G_{dm}(\alpha, \beta)\, PR}$$

G_{CEM} = 1 kW/m^2

E_D: Consumo expresado en kWh/día.

Para el cálculo, se utilizarán los valores de *PR* especificados en el punto 2.8 de este anexo.

3.5 Diseño del sistema

El instalador podrá elegir el tamaño del generador y del acumulador en función de las necesidades de autonomía del sistema, de la probabilidad de pérdida de carga requerida y cualquier otro factor que quiera considerar, respetando los límites estipulados en el PCT:

- La potencia nominal del generador será, como máximo, un 20 % superior al valor $P_{mp,\,min}$ para el caso general (ver 4.2.4 de este PTC).
- La autonomía mínima del sistema será de tres días.
- Como caso general, la capacidad nominal de la batería no excederá en 25 veces la corriente de cortocircuito en CEM del generador fotovoltaico. La autonomía del sistema se calculará mediante la expresión:

$$A = \frac{C_{20}\, PD_{max}\, \eta_{inv}\, \eta_{rb}}{L_D}$$

Donde:

A = Autonomía del sistema en días

C_{20} = Capacidad del acumulador en Ah (*)

PD_{max} = Profundidad de descarga máxima

η_{inv} = Rendimiento energético del inversor

η_{rb} = Rendimiento energético del acumulador + regulador

L_D = Consumo diario medio de la carga en Ah

III. Ejemplo de cálculo

1 Estudio de la carga

Se pretende electrificar una vivienda rural de una familia formada por 4 personas, situada en el término municipal de San Agustín de Guadalix (latitud = 41°). El servicio de energía eléctrica ofrecido a los usuarios está recogido en la tabla IV. El servicio proporcionado incluye la electrificación de la vivienda y un sistema de bombeo de agua (para uso personal y una pequeña granja).

Las pérdidas de autoconsumo de los equipos incluyen las del regulador (24 h × 1 W = 24 Wh) y las del inversor, para el que se ha estimado que funcionará 11 horas en vacío con un consumo medio de 2 W (11 h×2W = 22 Wh).

Tabla IV. Consumo diario de energía eléctrica.

Servicio	*Energía diaria* (Wh/día)
Iluminación	160
TV y radio	140
Frigorífico	350
Bombeo de agua	204
Autoconsumo de los equipos	46
E_D (Wh/día)	900

La bomba de agua extrae diariamente 1500 litros de un pozo (figura 3), cuya altura equivalente de bombeo se ha estimado en 20 metros, con una motobomba que tiene un rendimiento energético del 40 %. La prueba de bombeo realizada al pozo permitió obtener los siguientes parámetros:

H_{ST} = 15 metros

H_{DT} = 30 metros

Q_T = 10 m^3/h

(*) La utilización de C_{20} en lugar de la C_{100} lleva a sobredimensionar el acumulador un 25 %, pero se compensa con la pérdida de capacidad con el tiempo.

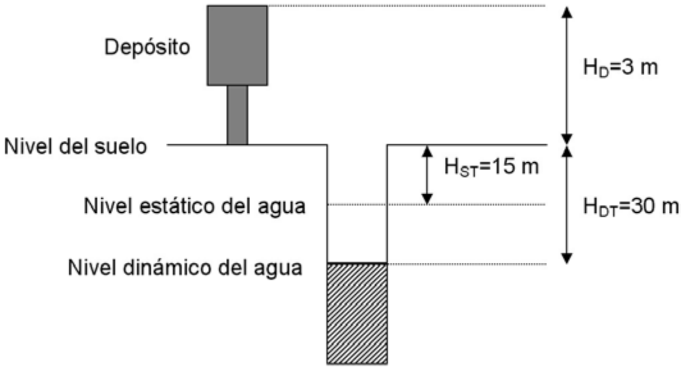

Fig. 3. Esquema del sistema de bombeo.

Por tanto, la energía eléctrica necesaria para el bombeo tiene como valor:

$E_{MB} = E_H /0_{MB}$ = (2,725 × 1,5 × 20)

/ 0,4 = 204 Wh/día La altura equivalente de bombeo se ha calculado

como:

H_{TE} = 3+15+[(30 –15) / 10] × (1, 5/

24)+2 = 3+15+0,094+2 ● 20 metros

Como se puede comprobar, el factor que corrige la variación dinámica del nivel del pozo es insignificante frente a la altura entre el nivel estático del agua y el depósito, debido a que el caudal bombeado es pequeño.

2 Diseño del sistema

Tabla V. Cálculo de la potencia mínima del generador.

Parámetro	*Unidades*	*Valor*	*Comentario*
Localidad		S. Agustín de Guadalix	
Latitud N		41°	
E_D	kWh/día	0,9	Consumo constante a lo largo del año
Período diseño		Diciembre	Mes de peor radiación y consumo constante (k = 1,7)
(" $_{opt}$, $$_{opt}$)		(0°, 51°)	
(", $)		(20°, 45°)	Orientación e inclinación del tejado
$G_{dm}(0)_{diciembre}$	kWh/(m² Adía)	1,67	Fuente: Instituto Nacional de Meteorología
FI		0,98	*FI* = 1 – [1,2 × 10 $^{-4}$($ – $$_{opt}$)^2 + 3,5 × 10 $^{-5}$ "^{2}]
FS		0,92	Sombra chimenea de un 8 % en diciembre
$PR_{diciembre}$		0,60	Eficiencia energética global del sistema
G_{dm}(", $)$_{diciembre}$	kWh/(m² Adía)	2,56	G_{dm}(", $)$_{diciembre}$ = $G_{dm}(0)_{diciembre}$ A *K* A *FI* A *FS*
$P_{mp,\,min}$	kWp	0,586	$P_{mp,\,min} = G_{dm}$ *E G* (Dαβ,) CEM *PR*

Para diseñar el generador se dispone de un módulo fotovoltaico cuyos parámetros en CEM tienen los siguientes valores:

- Potencia máxima = 110 Wp
- Corriente de cortocircuito = 6,76 A
- Corriente en el punto de máxima potencia = 6, 32 A
- Tensión de circuito abierto = 21,6 V
- Tensión en el punto de máxima potencia = 17,4 V

Se elige un generador de 660 Wp (formado por dos módulos en serie y tres ramas en paralelo) y un acumulador con una capacidad nominal de 340 Ah en 20 horas. La tensión nominal del sistema es de 24 V. Ambos valores se han elegido para asegurar una probabilidad de pérdida de carga inferior a 10^{-2} (*).

Las tensiones del regulador se ajustan de forma que la profundidad de descarga máxima sea del 70 %.

La eficiencia energética del inversor se estima en el 85 %, y la del regulador + acumulador en el 81%.

(*) Véase, por ejemplo, *Eduardo Lorenzo, "Electricidad Solar. Ingeniería de los Sistemas Fotovoltaicos". Progensa, 1994.*

Tabla VI

Parámetro	*Unidades*	*Valor*	*Comentario*
P_{mp}	Wp	660	$P_{mp} < 1{,}2\ P_{mp,\ min}$ (requisito obligatorio para el caso general)
C_{20}	Ah	340	Capacidad nominal del acumulador
PD_{max}		0,7	Profundidad de descarga máx. permitida por el regulador
0_{inv}		0,85	Rendimiento energético del inversor
0_{rb}		0,81	Rendimiento energético regulador-acumulador
V_{NOM}	V	24	Tensión nominal del acumulador
L_D	Ah	37,5	Consumo diario de la carga ($L_D = E_D / V_{NOM}$)
A	Días	4,37	Autonomía: $A = \frac{C_{20}\ PD_{max}\ \eta_{inv}\ \eta_{rb}}{L_D}$
C_{20} / I_{sc}	h	16,77	$C_{20} / I_{sc} < 25$ (requisito obligatorio para el caso general) I_{sc} (generador, CEM) = 20,28 A

Budget and economic analysis

7. Economical aspects of the project and list of elements:

Code	Element Name	Description	Amount	Price (€) with VAT per unit
Power supply and balance				
1.01	**TM- M672340**	Photovoltaic energy generation module.	52 modules	152,93
1.02	**Enair E30PRO 48V**	Wind turbine including its own regulator	1 module	6997,39
1.03	**SmartSolar 250/85**	Charge regulators for the battery system	2 modules	841
1.04	**Phoenix 48/5000**	Inverters	2 modules	3026,17
1.05	**Batteries RESU 10**	Energy storage systems	10 modules	4959,1
Connection Elements				
2.01	**Tecsun PV1-F 6 mm²**	Connection cables for the different solar panel strings and the house consumptions	356 meters	*
2.02	**Tecsun PV1-F 25 mm²**	Connection cables between turbine's regulator to battery system	4 meters	*
2.03	**Tecsun PV1-F 35 mm²**	Connection cables from combiner box to regulator and from regulator to battery system	56 meters	*
2.04	**Tecsun PV1-F 70 mm²**	Connection between battery system and inverters	4 meters	*
2.05	**Tecsun PV1-F 90 mm²**	Connection from the turbine to the charge regulator	40 meters	*
Protection elements				

3.01	**gPV fuse 15 A**	Cable protection	1	6,20
3.02	**gPV fuse 32 A**	Cable protection	14	23,26
3.03	**gPV fuse 50 A**	Cable protection	1	23,26
3.04	**gPV fuse 63 A**	Cable protection	1	23,26
3.05	**gPV fuse 80 A**	Cable protection	3	23,26
3.06	**gPV fuse 125 A**	Cable protection	1	23,26
3.07	**gPV fuse 250 A**	Cable protection	1	23,26
Supports				
4.01	**Solar panel support**	Roof Suport	52	**

*Prices and costs included in the Balance of the system.

**Included as well in the BOS.

On previous chapters of this case study we defined the total amount of needed elements for the hybrid installation, being the amount of elements needed for the installation:

TM- M672340	52 Panels
Enair E30PRO 48V	1 turbine + regulator
SmartSolar 250/85	2 charge regulators
Phoenix 48/5000	2 inverters in parallel
Batteries RESU 10	10 blocks

Table 62: Main elements to install at the hybrid system.

For the different calculations we will do in this chapter, the following parameters are needed to be defined:

Discount Rate: The gain or loss on an investment over a specified time period, expressed as a percentage of the investment's cost. For this case a discount rate of **5%** has been taken

O&M: Being the maintenance and operation of the system. For off-grid systems the annual O&M of **2%-6%** of the initial capital cost is taken , for this case study a rate of **2% .**

Investment period: The period of time taken into consideration when calculating the NPV and IRR of the investment. A period of 20 years has been taken.

VAT: Which is the value added tax. In Romania 2017, the VAT is 19 % of the product's price.

7.1. Budget of the installation

The cost of the elements in Table 63 will be :

	Price.exVAT(€)	PriceVAT(€)
Panels	6.683,04 €	7.952,82 €
Wind turbine	5.880,16 €	6.997,39 €
Inverters	5.086,00 €	6.052,34 €
Charge regulators	1.413,45 €	1.682,00 €
Battery system	41.673,55 €	49.591,53 €
Fuses	415,68 €	494,66 €
	Total price:	72.770,74 €

Table 63: Price with VAT of the system elements.

As we can see in off-grid systems the need of battery systems hugely increments the price. Now for the **Balance of System** (BOS) investment that the price includes:

Mounting system, installation, cables, infrastructure, transformer, grid connection, planning and documentation and any other elements.

For the off-grid system the transformer and grid connection will not form the part of the investment, as they are not needed. So taken data from ground-mounted PV systems in Germany [34] the cost for mounting is of **75 €/kWp**, Installation and DC-cabling costs are around **50 €/kWp** and infrastructure is **40 €/kWp**. Finally the compound cost of transformer, switchgear and planning is of **60 €/kWp**, so the price for planning and documentation is of **20 €/kWp.**

Engineering and construction is around **370 Euros/kWp** and Fees and permitting, are around **160 €/kWp**

Considering the wind turbine as part of the installed photovoltaic system we get that:

Installed power (kW)	Price/kWp (€/kWp)	Price (€)
20,68	715	14786

Table 64: BOS and additional cost.

A funding for the installation can be asked from the funding program **Casa verde** (Green house in English) for a total of 6000 Lei (**1500 €**) funding.

The total initial investment will be:

Elements price (€)	BOS+ others (€)	Funding (€)	Total (€)
72770,74	14786	-1500	86056,74

Table 65: Total initial investment

The yearly **O&M** cost is: **1619.767 €.**

Comparing the renewable solution to the standard connection to the electrical grid, it can be seen:

The distance between the closest connection point to the medium voltage (MV) network is 2 km far away (this distance is only the horizontal distance, not the upwards distance, due that the farm is located on a higher position respect to the closest population core)

The prices for a typical connection from an MV network, considering that the infrastructure required to connect the farm to the network is not installed:

- From MV to the location: $\mathbf{57900}\ €/\boldsymbol{km}$
- The price of the transformer from 20/0.4 Kv, 63kVA: $\mathbf{10500}\ €/\boldsymbol{Piece}$

Prices were given by **E·ON** company responsible of the installation of the electrical infrastructure in the area, the partner of **General Electric**. The prices are just estimated, and probably in the case scenario where the traditional grid connection was chosen, the price could be higher due to the difficulties on the whole line installation along the area (uphill, forest, mud etc…)

Therefore the initial investment from the connection to the normal grid will be a total of:

$$TotalPrice_{StandardConnection} = 2\ km * 57900 \frac{€}{km} + 10500 \frac{€}{piece} = \mathbf{126300}\ €$$

We can see that the price is higher than the proposed installation for this case study.

7.2. Payback, IRR and NPV

The payback from the installation is calculated with the following formula:

$$Payback\ period = \frac{Initial\ investment}{Anual\ cash\ flows} \quad \textbf{(40)}$$

Where the annual cash flows will be from the saving from not used diesel generator:

$$CashFlow = LitresDieselSaved * PriceDiesel - O\&M \quad \textbf{(41)}$$

Where the yearly litres of diesel saved (see Air pollution and greenhouse gas emissions) are:

Litres Diesel Saved : 9357,647 Liters

Price Diesel: The average of diesel price in Romania is around **1€/liter**.

$$CashFlow = 9357.648 \frac{€}{Year} - 1619.76 \frac{€}{year} = 7737.88\ €/year$$

Therefore the Payback period will be:

$$Payback\ period = \frac{86056{,}74\ €}{7737{,}88\ \frac{€}{Year}} = 11{,}121\ Years$$

NPV and IRR:

The equation for the **Net Present Value** is:

$$NPV = -I_o + \sum_{t=1}^{n} \frac{CashFlow}{(1+DiscountRate)^t} \quad \textbf{(42)}$$

Where:

Io: Is the initial investment

N: is the investment period

A **positive NPV** means that the inversion is profitable and should be accepted, because we will get a profit because the return rate is higher than the discount rate

A **NPV=0** means that it should be accepted with conditions, since it does not bring neither benefit nor loss.

A **negative NPV** should be rejected

As for Internal Return Rate (**IRR)**:

It is the rate when NPV equals to zero.

$$NPV = -I_o + \sum_{t=1}^{n} \frac{CashFlow}{(1+IRR)^t} = 0 \quad \textbf{(43)}$$

A **positive internal rate** means, that IRR is bigger than the discount rate, it would mean that the return rate from the inversion is greater than the discount rate considered, and you gain profit from the investment you have invested in. The project should be accepted.

An **equal IRR** would mean that you neither lose neither win money, the project should be accepted.

When the **IRR is smaller** than the Discount rate, it means, that the inversion is not profitable, should be discarded.

The NPV for the project is of **9.880,43 €** and a IRR of **6%** which is higher than the considered Discount rate of **5% (**see Table 64) therefore the investment is expected to be profitable. At the 17 year mark the installation starts providing benefit and returning the investment.

	SAVINGS	COST	PROFITABILITY		
	FuelPriceSaved (€/year)	O&M (€/year)	Cash-Flow	Cumulative Cash-Flow	NPV (€)
0			- 86,056,74 €		
1	9357,648	1619,76	7,737,89 €	7,737,89 €	-74,940,31 €
2	9357,648	1619,76	7,737,89 €	15,475,78 €	-68,256,03 €
3	9357,648	1619,76	7,737,89 €	23,213,66 €	-61,890,05 €
4	9357,648	1619,76	7,737,89 €	30,951,55 €	-55,827,21 €
5	9357,648	1619,76	7,737,89 €	38,689,44 €	-50,053,08 €
6	9357,648	1619,76	7,737,89 €	46,427,33 €	-44,553,91 €
7	9357,648	1619,76	7,737,89 €	54,165,22 €	-39,316,60 €
8	9357,648	1619,76	7,737,89 €	61,903,10 €	-34,328,69 €
9	9357,648	1619,76	7,737,89 €	69,640,99 €	-29,578,30 €
10	9357,648	1619,76	7,737,89 €	77,378,88 €	-25,054,11 €
11	9357,648	1619,76	7,737,89 €	85,116,77 €	-20,745,37 €
12	9357,648	1619,76	7,737,89 €	92,854,66 €	-16,641,80 €
13	9357,648	1619,76	7,737,89 €	100,592,54 €	-12,733,64 €
14	9357,648	1619,76	7,737,89 €	108,330,43 €	-9,011,59 €
15	9357,648	1619,76	7,737,89 €	116,068,32 €	-5,466,77 €
16	9357,648	1619,76	7,737,89 €	123,806,21 €	-2,090,76 €
17	9357,648	1619,76	7,737,89 €	131,544,10 €	1,124,50 €
18	9357,648	1619,76	7,737,89 €	139,281,98 €	4,186,64 €
19	9357,648	1619,76	7,737,89 €	147,019,87 €	7,102,97 €
20	9357,648	1619,76	7,737,89 €	154,757,76 €	9,880,43 €
				154,757,76 €	9,880,43 €
		Discount Rate:	0,05	IRR: 6%	

Table 66: NPV and IRR of the system. Source: Own creation

Project plans

8. Project Plans:

Figure 40: Distribution plan

On Figure 40 is showed an aerial view of the farm, and the suggested installation location for the system:

In red the location of the solar panels.

In orange the location of the wind turbine.

In green the location of the different elements (charge regulators, inverters) and the battery system.